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Evaluation of Sand Filter Performance

by

Michael E. Barrett, Ph.D., P.E., D.WRE

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Center for Research in Water Resources
Bureau of Engineering Research
The University of Texas at Austin

Table of Contents

List of Figures

List of Tables

1 Introduction

This report presents an analysis of water quality data collected by the City of Austin between 1985 and 1997 from various stormwater filtration facilities located in the Austin area. The objective of the analysis is to determine how facility design and storm characteristics affect pollutant removal. Of particular interest are residence time, water depth over the filter, pretreatment, and temporal patterns of pollutant discharge.

The facilities where the water quality data were collected include Jollyville, Highwood, Barton Creek Square Mall, Brodie Oaks, and Barton Ridge. The designs of these facilities vary significantly and their distinguishing characteristics are shown in Table 1.

Table 1 Description of Stormwater Filtration Facilities

	Jollyville	**Highwood**	**Barton Creek Square Mall**	**Barton Ridge**	**Brodie Oaks**
Off/On-Line	Off-line	On-Line	On-Line	Off-Line	On-Line
Pretreatment	None	None	None	Sedimentation Basin	Wet Pond (used for irrigation)
Water Quality Volume WQV (cu.ft.)	17,000	2,970	143,000	7,000	NA
Water Quality Volume WQV (in.)	0.5	0.23	0.5	0.65	NA
Design Drawdown Time DDT (hr)	24	NA	24	40	NA
Filtration Media Surface Area Af (sq.ft.)	2,600	2,750	21,780	390	~5,500
Depth of Filtration Media D (ft.)	2.5	Varies	2.5	1.5	NA
Maximum Ponding Depth over Sand Media H (ft)	3.9	~1.0	4	2.0	~15

The five sand filters analyzed in this study are all believed to have essentially the same media, which is a quartz and feldspar sand that has a size distribution consistent with fine aggregate as defined in ASTM C-33. However, there are substantial differences in the maximum water level over the filter media, which range from roughly one foot (Highwood) to approximately 15 feet (Brodie Oaks). One potentially significant difference is that most of the sites have a filter profile like that shown in Figure 1. Highwood, on the other hand has a filter constructed as shown in Figure 2, which provides much less filter volume.

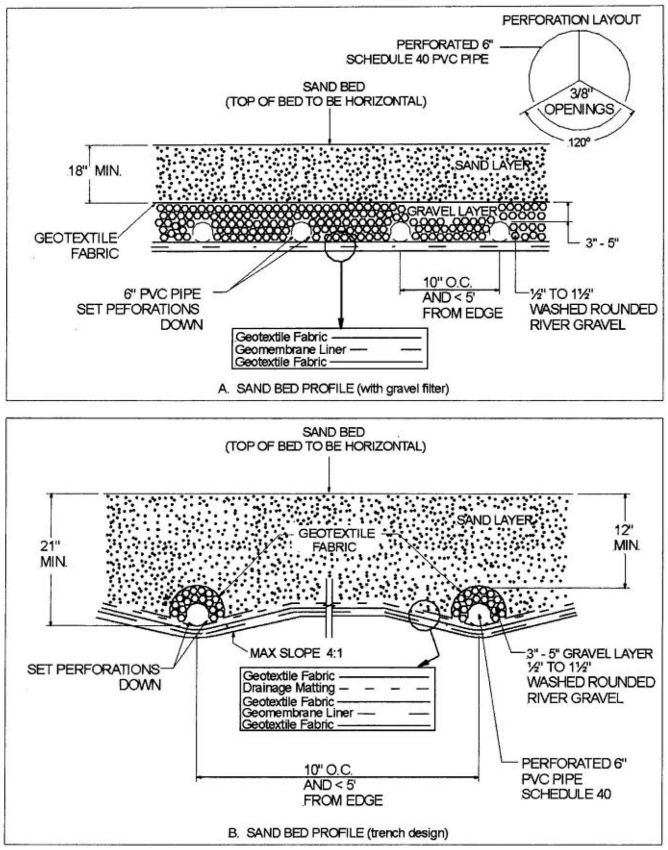

Figure 1 Typical Austin Sand Filter Bed

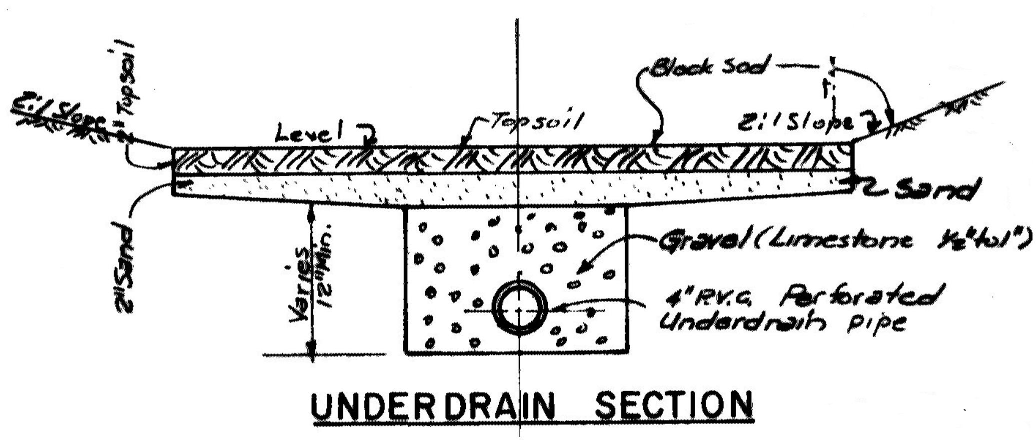

Figure 2 Highwood Filter Bed

One item of interest is whether there are pollutants for which reaction kinetics limit their removal. This is primarily of interest for dissolved constituents that might adsorb to, or otherwise react with, the filter media. Dissolved concentrations are available for nitrogen; however, there is no information for or any of the metals and only limited data for dissolved phosphorus. Consequently, variation in removal for metals could be the result of either changes in the removal or variation in fraction of the dissolved phase in the influent runoff. Nevertheless residence times were calculated for a number of events and compared to both effluent quality and removal efficiency. The residence time was calculated as the time difference between the centroids of the influent and effluent hydrographs.

Another consideration in analyzing attributing changes in effluent water quality to physical processes occurring in the filter is differentiating between variation resulting from physical processes and those relating to sample collection and analysis. Substantial variation in reported constituent concentrations when identical samples are sent to multiple laboratories is not uncommon, even among certified laboratories. This is even more of an issue when the reported concentrations are near the method detection limit. In these cases very small absolute differences might still represent a substantial percentage difference from the reported amounts. This occurs most frequently for metals (especially copper in this dataset).

Sample collection methodology can also result in differences between actual and estimated storm concentrations. Most of the water quality data consists of multiple individual samples taken during an event which are later averaged with a weight based on the volume assigned to each sample. Two issues have been observed in the data that suggests significant errors might have occurred. For many storm events at the facilities there is not a consistent relationship between influent and effluent volumes; consequently there are substantial mass balance errors. One might expect effluent volumes to be about the same as influent volumes since the basins are lined or one might think that the effluent volumes should be somewhat less because of runoff retained in the pores of the filter media and subsequently lost to evaporation between events. What is actually observed is that the ratio of influent to effluent volumes ranges from 3.45 to 0.14, which means that some error in the calculated concentrations is likely.

The second issue related to sample collections is the event mean concentration (EMC) is calculated based on as few as three individual samples. Many of the constituents exhibit a pronounced first flush effect, which is particularly evident in the storms where at least six individual samples were collected. In the cases where only three samples were collected the initial sample concentration measured at the beginning of the event, when concentrations are briefly elevated, are assigned to a larger volume of runoff than is likely warranted. This results in the calculated EMC being larger than the actual concentration.

1.1 Mathematical Modeling of Sand Filter Performance

Particle removal in sand filters is conventionally modeled as a combination of three attachment mechanisms, which are illustrated in Figure 3. These mechanisms include capture by sedimentation (particle is moving faster than the fluid due to gravity), interception (particle momentum causes collision), and diffusion (Brownian motion results in particle collision).

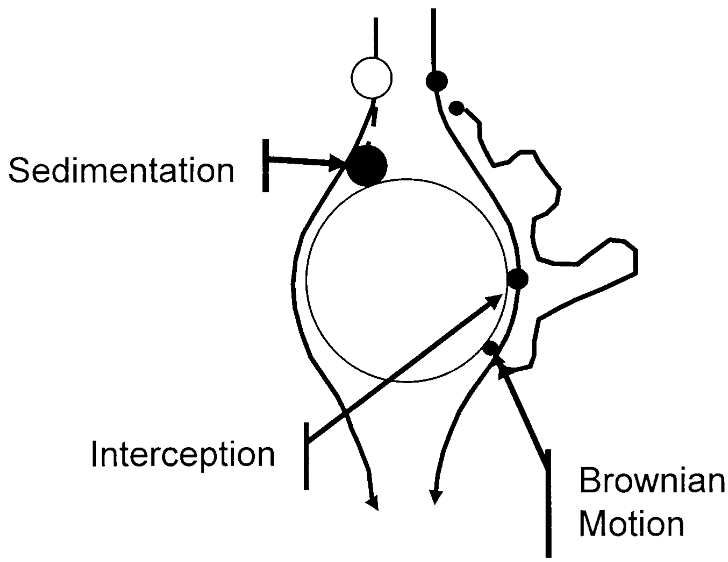

Figure 3 Mechanisms of Particle Capture in Filters

The classic model consists of quantifying the removal associated with a single filter media particle and then integrating over the entire volume of the filter. This results in the classic formulation (Yao, et al. 1971):

$$T_e = 1 - \exp\left[-\frac{3}{2}\left(\frac{(1-\varepsilon)\alpha\eta}{d_c}\right)L\right]$$

Where:

T_e = Trapping efficiency
ε = Filter porosity
α = Collision frequency
η = Attachment efficiency
d_c = Characteristic diameter of the filter media particles
L = filter thickness

This formulation has two major empirical factors η and α. The first of these refers to the rate at which particles in the fluid strike a collector in the filter, while the second is the rate at which particles that strike the collector become attached. Consequently, it is fairly easy to make the model agree with measured data for an individual event.

There are several issues with the use of this model for analyzing performance of stormwater sand filters. First of all, the model gives the same results for all events since it does not include information related to changes in particle size distribution in the runoff and it does not account changes in performance resulting from accumulation of particles within the filter. Perhaps the biggest shortcoming is that this conceptual model does not address particle removal via straining, which is generally avoided in engineered systems to reduce headloss.

Straining is believed to be an important removal process when:

- Flow rates are low (<300 ft/d) and solids flux is high
- Ratio of particle size to media size is >0.2
- Particles in the fluid have a diameter greater than 100 μm.

Sand filters used for stormwater treatment are considered to be slow sand filters and the typical flow rates are about 1/10 of the critical value for straining. In addition, many of the particles in stormwater are relatively large; consequently, straining may account of between 50-80% of particle removal when the filter is clean. As material accumulates on the surface even smaller particles would be subject to removal by straining, so that eventually straining would likely account for virtually all particle removal. Consequently, conventional mathematical formulations that described filter performance are not likely to be relevant in this application.

1.2 Statistical Analysis

One question that inevitably arises in evaluating BMP performance is the appropriate way to calculate mean influent and effluent concentrations. Since the data are often lognormally distributed, one might choose a method suitable for this type of data. Gilbert (1987) provides two methods to calculated the mean values for lognormal data. One of these provides the precise value, but involves an infinite series. The second method, which has been used by a number of authors, involves the simpler estimating method shown below.

$$a = e^{(\mu + s^2/2)}$$

where a is the mean of the Event Mean Concentrations (EMCs), μ is the mean and s^2 the variance of the log transformed EMCs.

Gilbert also recommends that in cases where the data are not highly skewed (Coefficient of variation (COV) less than 1.2) that the arithmetic mean is the preferred measure of central tendency. The COV for all the measured data are presented in Table 2 and it is evident that the majority of the data have a COV of much less than 1.2. Consequently, the arithmetic mean is used to calculate average influent and effluent concentrations for the sand filters.

Table 2 Coefficient of Variation for Monitoring Data

Constituent	Influent COV	Effluent COV
TSS	1.26	0.99
Total Zn	0.79	0.68
Total Cu	0.79	0.74
Pb	0.82	0.71
Total P	0.89	0.71
Diss P	0.79	0.82
TKN	0.70	0.70
NO_{2+3}	0.59	0.62
BOD	0.87	1.20
COD	0.79	0.72
Fecal C.	1.53	1.47
Fecal Strep	1.35	1.70

A variety of statistical techniques are available to determining whether differences in influent and effluent concentrations are significant. A popular method for independent data is the t-test, which compares the means of two sample groups. This is probably the least discriminating test and an assumption of the test is that the underlying data are normally distributed. Given that many water quality datasets are lognormal, the test can be applied more correctly to the transformed data. Nevertheless, the test is not very sensitive to the distribution of the data.

Another test that works very well for BMP performance data is the paired t-test, which is very powerful for identifying differences. This test determines if the difference between the influent and effluent concentrations of paired samples is significantly different than zero. This test makes no assumptions about the distribution of the actual data, but assumes that the differences between the paired samples are normally distributed; however, like the t-test, it is not very sensitive to this assumption. It is not uncommon to have effluent concentrations for some events exceed the influent concentrations, resulting in negative numbers, so a log transformation is not possible in this case.

When the differences in the paired samples are highly non-normal, it may be appropriate to use the nonparametric equivalent of the paired t-test, which is the Wilcoxon Signed Rank Test (SRT). This test determines whether the median of the paired differences is significantly different than zero. Both the paired t-test and Wilcoxon test were used to determine whether the influent and effluent concentrations were significantly different.

The influent and effluent quality data from each of the sites was analyzed individually and pooled to determine removal efficiency. Because of the variety of distributions, the Wilcoxon SRT was the primary tool to determine whether removals were significant.

The following sections describe the detailed performance of the filtrations systems for each of the constituents individually. In these sections, the performance for each constituent is calculated individually. In addition, data are provided to:

- Summarize the influent and effluent concentrations with boxplots
- Determine the distribution of the data
- Identify performance for each facility
- Display how concentrations vary during a storm event
- Relate discharge concentrations to influent concentrations
- Related discharge concentrations to residence time

2 Total Suspended Solids (TSS) Performance

The TSS data for each site were first analyzed to determine whether their distribution was normal or lognormal. Table 3 presents the results of this analysis. Where both distributions are shown, neither could be rejected by the null hypothesis. Question marks indicate that the data did not follow either of these common distributions.

Table 3 Statistical Distribution of TSS Data for Each Site

	Barton Mall	Barton Ridge	Brodie Oaks	Highwood	Jollyville	All sites
Influent	Normal	?	Normal/Lognormal	Lognormal	?	?
Effluent	Normal/Lognormal	Lognormal	Lognormal	Lognormal	?	?

Figure 4 presents the cumulative probability plot for both influent and effluent concentrations for TSS for all the filters combined using only paired data. Note that the TSS influent concentration distribution is statistically different from the lognormal distribution (and the normal distribution as well).

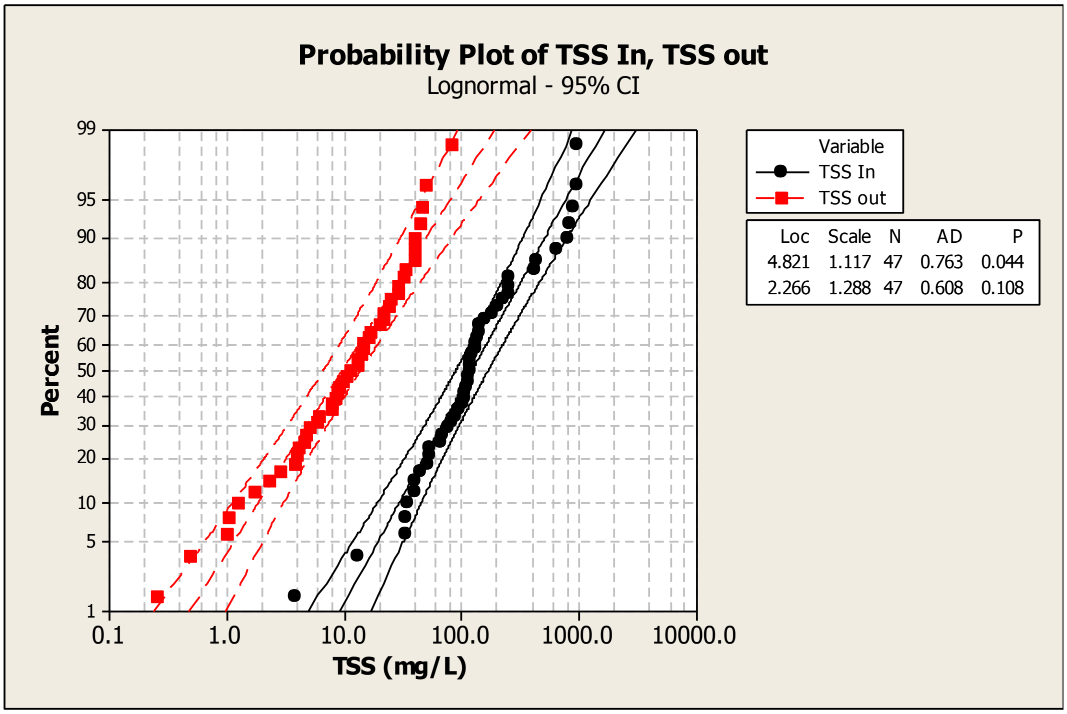

Figure 4 TSS Influent and Effluent Probability Plots for all Sites Combined

A boxplot of influent TSS concentrations for the five sand filters is presented in Figure 5 and ANOVA indicates that these concentrations are significantly different ($p < 0.000$). Figure 6 presents a boxplot of TSS discharge concentrations for the five sand filters. An ANOVA analysis indicates there is no significant differences in the average discharge concentrations ($p = 0.394$), despite very different influent concentrations, facility design (pretreatment or not), maximum water depth, and other factors. The mean concentrations at Barton Ridge and Brodie Oaks are slightly higher than the other sites; however, median concentrations are almost identical. These sites have very different maximum water depths, only a couple of feet at Barton Ridge compared with about 15 feet at Brodie Oaks. We can, therefore, conclude that water depth has little effect on average particle removal.

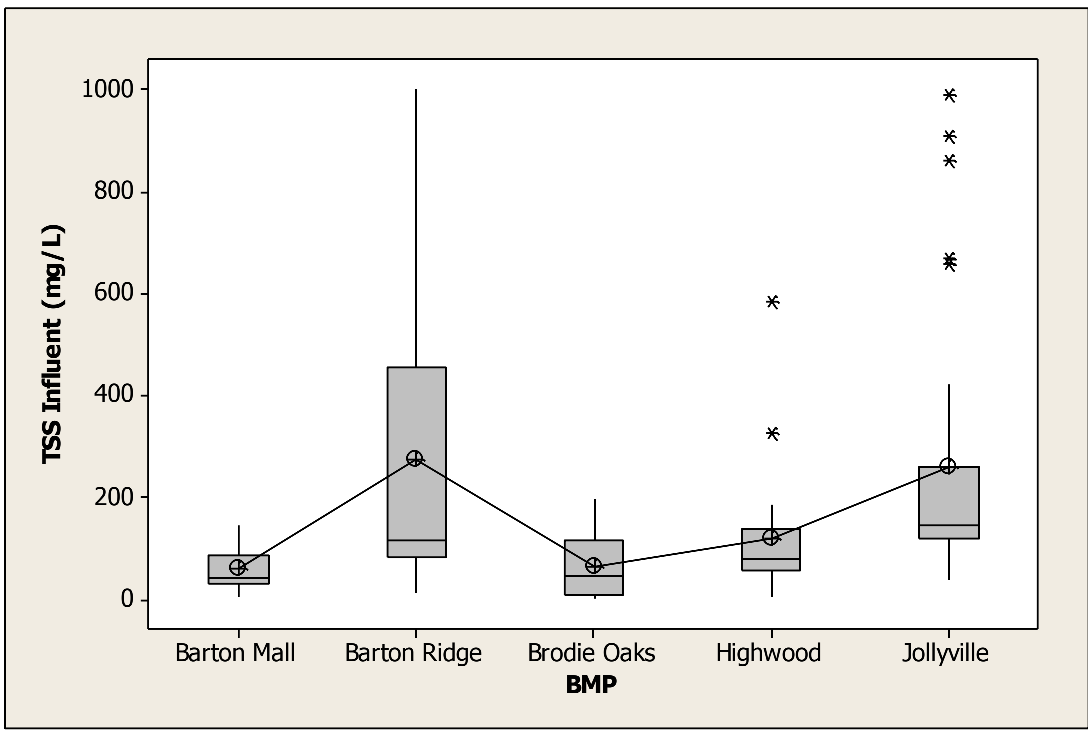

Figure 5 Boxplot Influent TSS Concentrations

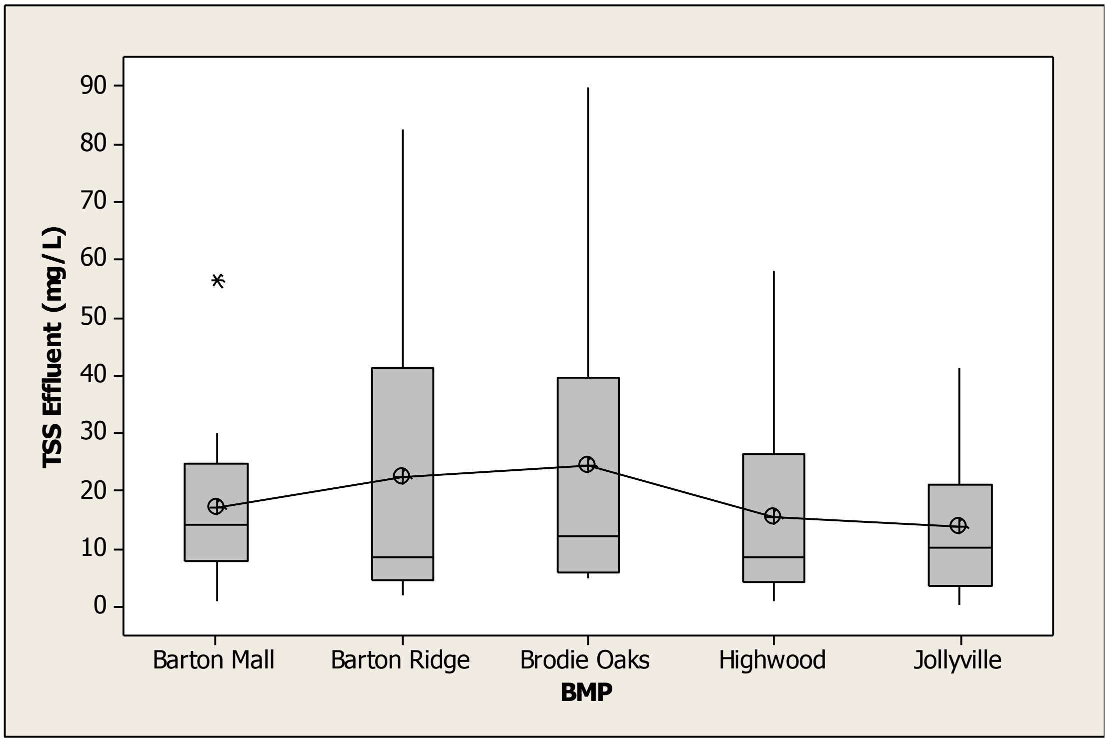

Figure 6 Boxplot of TSS Discharge Concentrations (all data)

Table 4 presents arithmetic mean concentrations for the individual sites based on storms where data were available for both the influent and effluent. TSS removal was statistically significant at all locations; however the efficiency ratio varied substantially, despite the very similar effluent quality produced. It is apparent from the table how influent concentrations strongly affect this ratio, with the cleanest sites have apparently the worst performance and the dirtiest sites the best. Consequently, efficiency ratio is not recommended for comparing BMP performance.

Table 4 TSS Concentrations for Individual Sites based on Paired Data

Site	EMC in	EMC out	Efficiency Ratio	Wilcoxon SRT
Barton Mall	74	13	82	0.002
Barton Ridge	286	25	91	0.070
Brodie Oaks	69	18	74	0.125
Highwood	101	18	82	0.022
Jollyville	304	16	95	<0.000
All Sites	198	17	91	<0.000

Filtration is primarily a particle removal process and its efficiency is a function of several variables. These include the properties of the filtration media, including size distribution and surface chemistry. Similarly, characteristics for the particles in runoff play an equally important role. Finally, flow rates through the filters can often have a substantial impact on particle retention. These variables determine how well particles are removed within the filter either through straining or surface attachment.

A previous study of particle removal in sand filters (TxDOT full sedimentation filter at Loop 360 and Barton Creek) found that virtually all the mass associated with particles with diameters about 3 μm were removed (Figure 7). These particles account for the vast majority of TSS, which suggests that we should observe relatively constant effluent quality regardless of the concentrations in untreated runoff (Karamalegos et al., 2005). Pretreatment (either in a dry sedimentation basin or wet pond) would be expected to primarily reduce the maintenance requirements of the filters rather than affecting the quality of the system discharge. Consequently, one would expect that any differences observed in discharge quality would be associated with the maximum water depth, which controls flow rates through the filter.

This conclusion is reinforced when one looks at a plot of discharge (an indirect measurement of water depth and loading rate) versus TSS effluent concentration for Brodie Oaks, which has the highest potential water level of all the filters (Figure 8). This plot shows that the two storms with the highest TSS discharge concentrations were produced by storms that had the two lowest hydraulic loading rates. It is important to note that the hydraulic loading rate for stormwater filters (3 ft/d or 0.016 gal/min*ft^2) is far lower than that used in applications such as water treatment plants (3 gal/min*ft^2 or 576 ft/d)

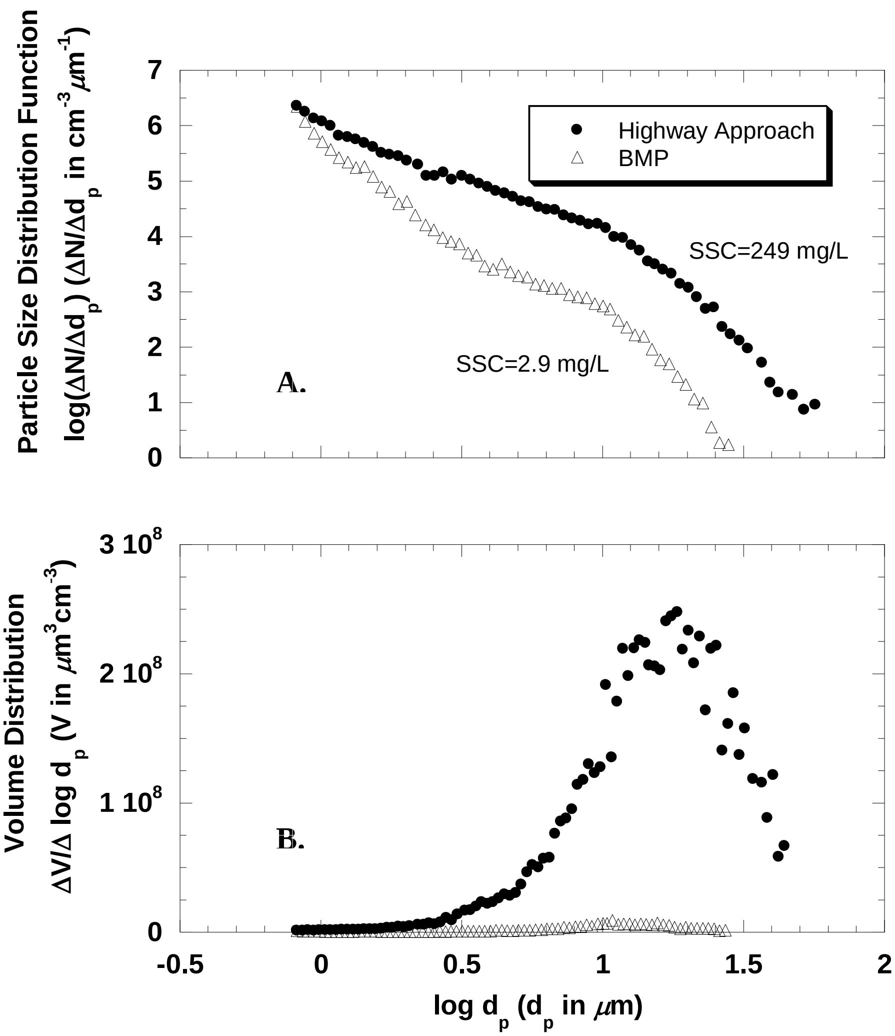

Figure 7 ***(A)*** **Particle Size Distribution Function and** ***(B)*** **Volume Distribution**

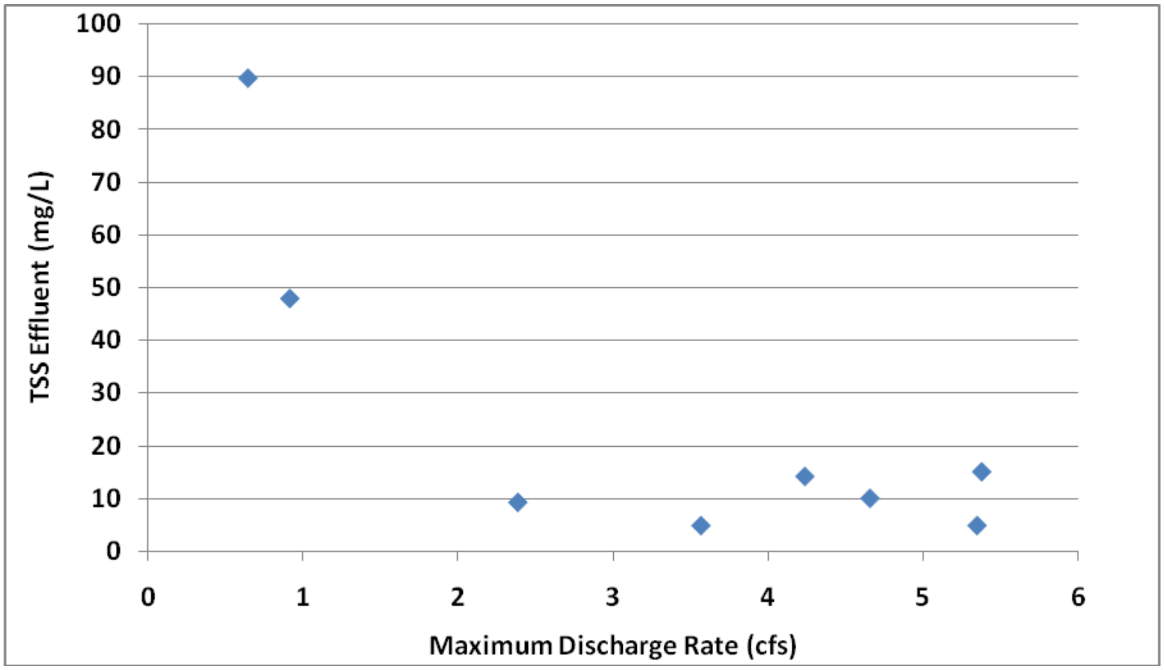

Figure 8 Comparison of Maximum Discharge Rate and Average TSS Discharge Concentration at Brodie Oaks

The two storms in Figure 8 with the elevated concentrations were also the smallest events, which suggests that what is observed is a first flush effect that is not diluted by runoff that would have occurred subsequently in a larger event.

For many BMPs, the effluent quality is affected by the influent concentration. Consequently, a plot of influent versus effluent TSS concentrations using data from all the sites was prepared and linear regression performed (Figure 9). The R^2 for the regression is 0.44, which is relatively high for stormwater analyses; consequently, discharge concentration can be predicted based on the influent concentration. This figure indicates that discharge concentrations tend to increase gradually with higher influent concentrations. The relatively mild slope suggests that higher runoff concentrations are mostly associated with an increase in the larger particles, which are all effectively removed by the filter. This is consistent with the results of a study of the effect of BMPs on particle size distributions of highway runoff (Karamalegos, 2005). A previous study of sand filter performance (Barrett, 2003) found no statistical relationship between influent and effluent concentration; however, there was only one influent concentration in that study that was relatively high (420 mg/L). If one considers only the concentrations of less than 400 mg/L in the COA data, then one reaches the same conclusion that effluent concentration is independent of influent concentration.

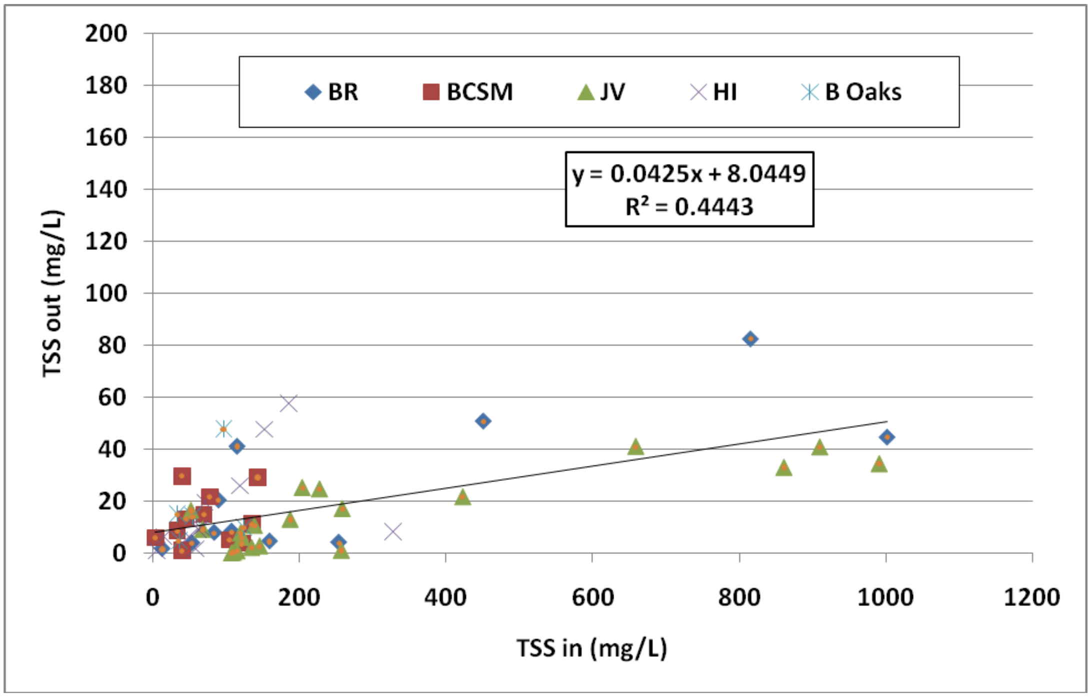

Figure 9 Influent and Effluent TSS concentrations for all Sites

When the sites are analyzed individually only two the facilities have significant relationships between influent and effluent TSS concentrations, Barton Ridge and Jollyville. Graphs for these two sites are presented in Figure 10 and Figure 11, respectively. The other sites do not appear to have the range of influent concentrations necessary to observe a statistically significant relationship.

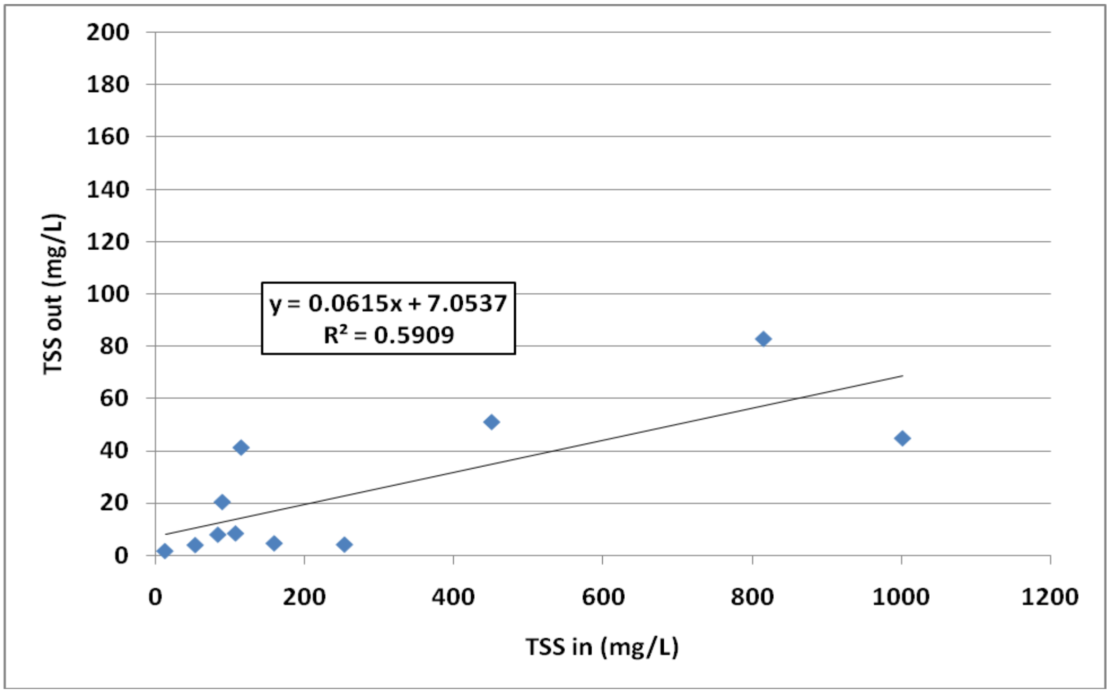

Figure 10 Influent and Effluent TSS concentrations for Barton Ridge

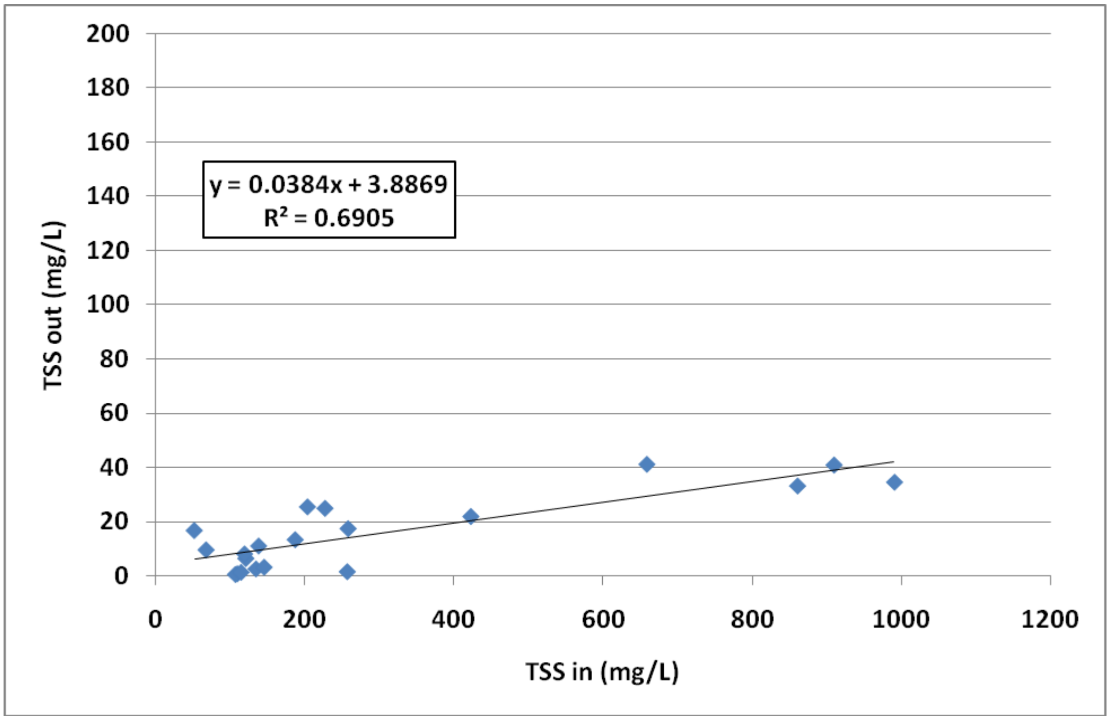

Figure 11 Influent and Effluent TSS concentrations for Jollyville

One interesting phenomenon related to particle removal in filters is the pattern of concentrations of individual aliquots taken during a single event. Figure 12 presents the individual concentrations observed at Jollyville. There is an unmistakable “first flush” type pattern evident, which is also observed at every other site. There are two potential explanations for this pattern. One is that subsequent events mobilize material retained in and on the filter bed from previous events and transport that material through the filter. This seems unlikely since visual observation of the filter media profile consistently indicates that most material is retained in the top few inches of the filter. Consequently, it seems unlikely that an initial storm surge could transport concentrations as high as 200 mg/L through the filter.

A second explanation is that some amount of the fine material that is transported through the filter, settles out in the underdrain during the waning hours of the previous event. This material could then be remobilized during the high flows in the initial part of the subsequent event producing the first flush pattern that we observe. This is easily testable by flushing out the underdrain through the cleanout ports and observing whether the following event produces this same temporal pattern in concentration.

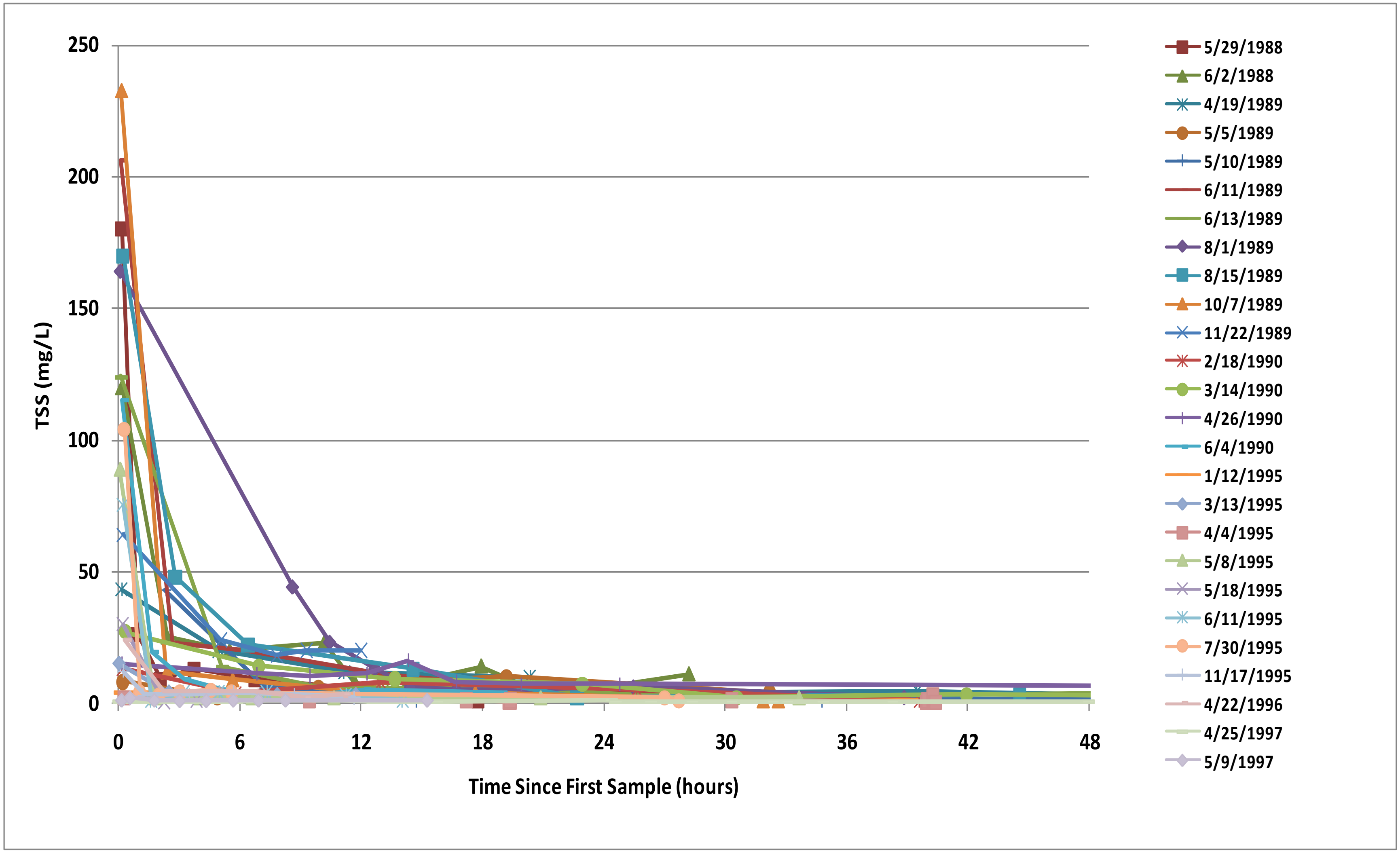

Figure 12 Jollyville Sand Filter TSS Discharge Time Series

An accumulation of fine grained material often occurs within the upper few inches of filters and on the surface (the Schmutzdecke). One might conclude that this finer grained material would increase the TSS removal by providing additional sites where particles could attach and reducing the size of the pore throats increasing the efficiency of particle straining. To test this hypothesis, a multiple regression analysis was performed for selected facilities. The regression used date and TSS influent concentrations as independent variables. It was found that time was not a significant predictor of Jollyville ($p = 0.931$) or Barton Ridge ($p = 0.494$) effluent concentrations. Unexpectedly, the TSS concentration in the discharge of Barton Creek Square Mall grew significantly worse through time ($p = 0.005$) and unlike the other systems was independent of influent concentration (Figure 13). Similar statistical tests were also performed for TP and Zn to try to assess whether any change in dissolved concentrations occurred; however, neither of these constituents exhibited a significant trend with time ($p = 0.914$ and $p = 0.290$).

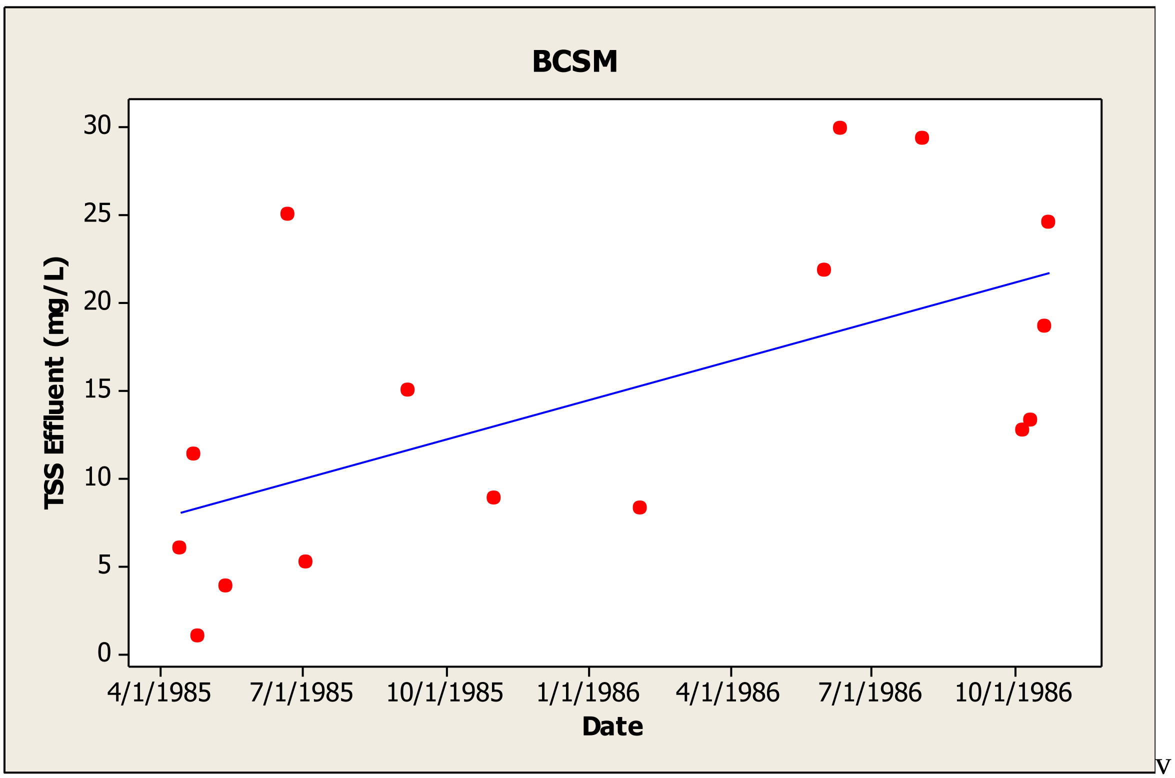

Figure 13 Relationship between TSS Discharge Quality and Time for Barton Creek Square Mall

The observation that TSS removal does not improve as a filter ages and straining becomes more dominant suggests that the removal processes change through time. Early in the life of the filter a substantial amount of particle removal likely occurs through deep bed filtration where sedimentation, interception, and Brownian motion are the dominant processes. As the filter accumulates material near the surface, straining becomes more important and near the end of the filter life is probably the dominant particle removal mechanism. Consequently, we infer a shift in the processes for particle removal through time, but little change in overall efficiency.

Hydraulic residence time (HRT) is another variable that might be expected to affect the removal of selected pollutants. HRT was calculated for events at the Jollyville site as the difference between influent and effluent hydrographs. During many events there were substantial differences between inflow and discharge volumes which add some noise to the analysis. Figure 14 presents a graph of TSS removal versus HRT. It is apparent that HRT has no discernable effect on performance. A regression analysis was also performed to determine if TSS discharge concentration was a function of HRT (controlling for influent concentration); however, HRT was not a significant predictor ($p = 0.156$).

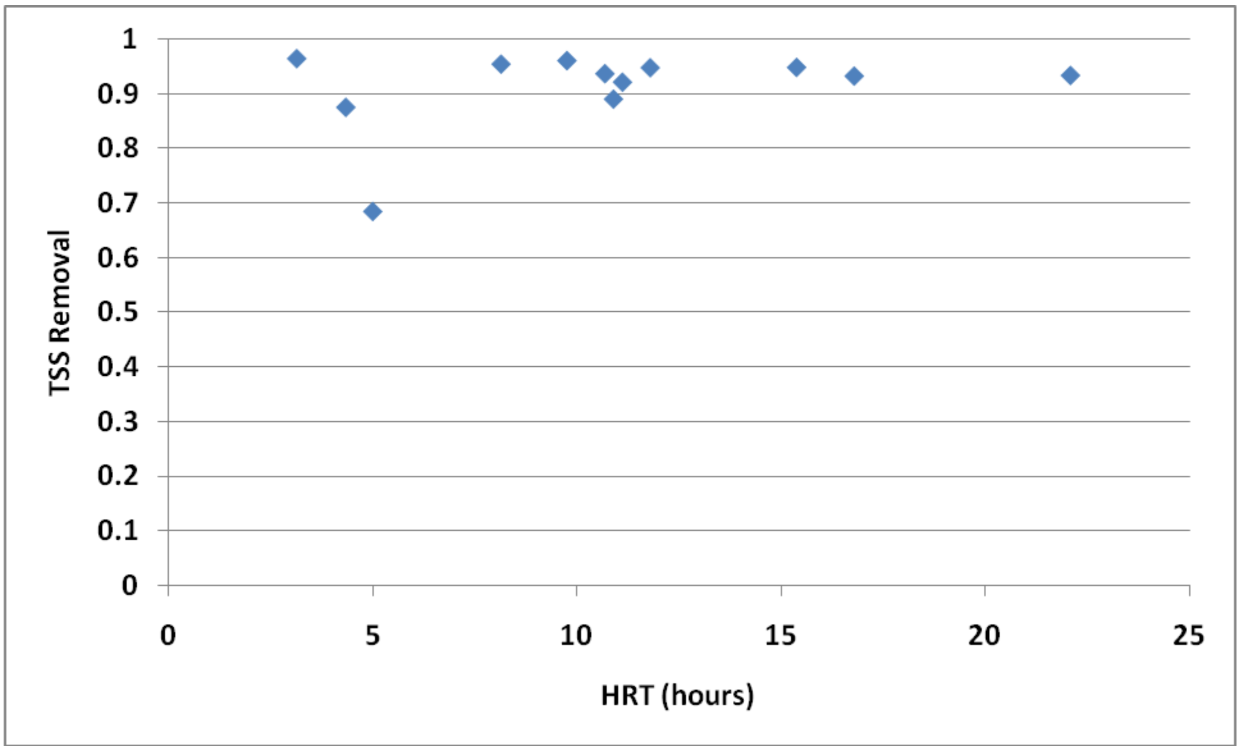

Figure 14 Comparison of TSS removal to Hydraulic Residence Time

Barton Ridge is the only one of the sites that includes samples collected from the discharge of the sedimentation basin, which allows a calculation of the TSS mass removed by sedimentation as opposed to filtration. Using the mean of the individual storm removals, the data indicate that about 68% of the TSS is removed by sedimentation, while the filter basin removes an additional 75% of the remainder for a total removal by the system of approximately 90%. It should be noted that material coarse enough to be removed by sedimentation, would also likely be completely removed by the filtration unit even if no pretreatment were provided.

TSS Conclusions:

1. Discharge TSS concentrations were similar for all facilities, so design factors such as pretreatment, maximum water depth, and filter area apparently have little effect on particle removal.

2. The upper bound of diameter for particles that can pass through the filter is about 30 μm.

3. All the facilities evaluated (even Brodie Oaks, which includes a wet pond for pretreatment) had a distinct first flush that might be attributed to the accumulation of sediment in the underdrain system at the end of storm events.

4. TSS removal was not a function of time, indicating that the accumulation of material on and within the filter had little impact on particle removal, but suggests that the removal processes change with time.

5. Hydraulic residence time did not affect either removal efficiency or discharge concentration.

6. Pretreatment reduces the total sediment load to the filter by about 65-70%, but may not material extend the life of the filter since this sediment likely is fairly coarse, which would result in little loss of permeability if it accumulated on the surface of the filter.

3 Volatile Suspended Solids (VSS) Performance

There is very little data on the removal of VSS in sand filters, since data are available for only two sites, Barton Ridge and Jollyville. The data were initially examined to determine their distribution, which is mostly lognormal as shown in Table 5.

Table 5 Statistical Distribution of VSS Data for Each Site

	Barton Ridge	Jollyville	All sites
Influent	Lognormal	Lognormal	Lognormal
Effluent	Lognormal	Normal/ Lognormal	Lognormal

Figure 15 presents the cumulative probability plots of VSS influent and effluent concentrations for the pooled data from both sites. The distributions are very distinct, which confirms that substantial reduction of VSS does, in fact, occur.

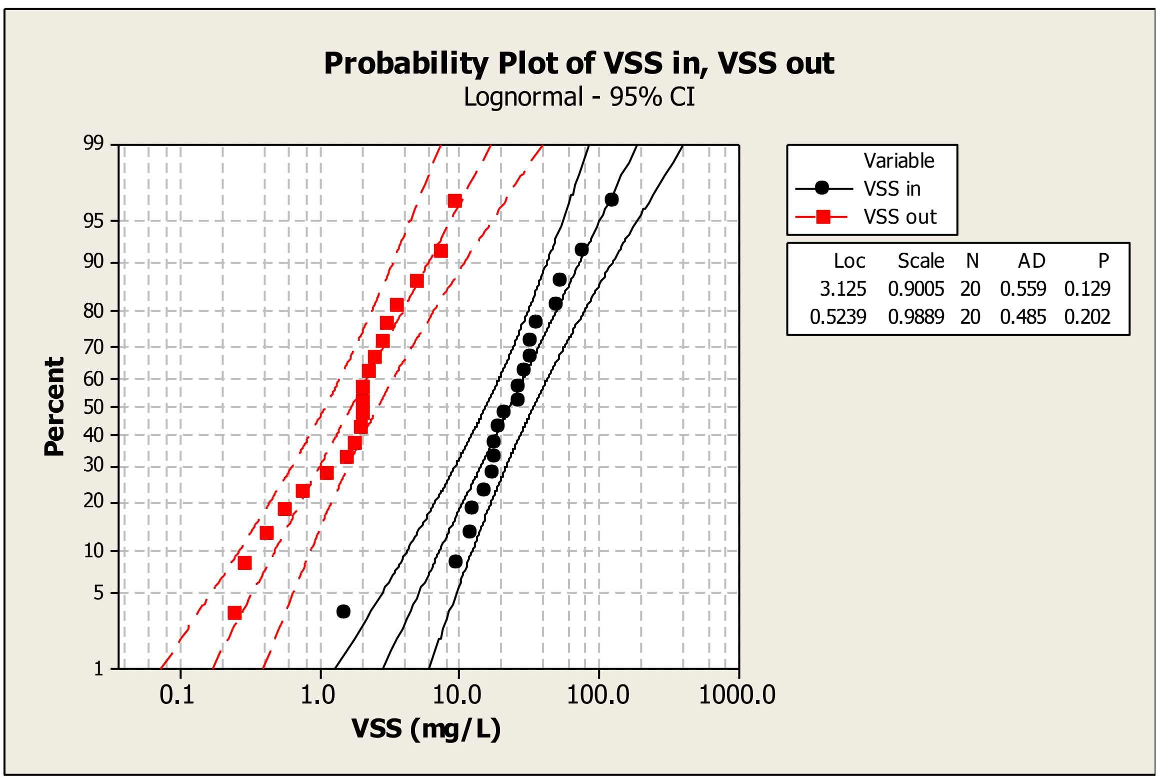

Figure 15 Probability Plots of VSS Influent and Effluent

Boxplots of influent and effluent concentrations at those sites are presented in Figure 16 and Figure 17, respectively. The influent concentrations at the two sites are not significantly different ($p = 0.674$); however, the effluent concentrations are significantly lower at Jollyville ($p = 0.003$). This somewhat unexpected since the Barton Ridge site includes pretreatment as well as infiltration, while Jollyville does not.

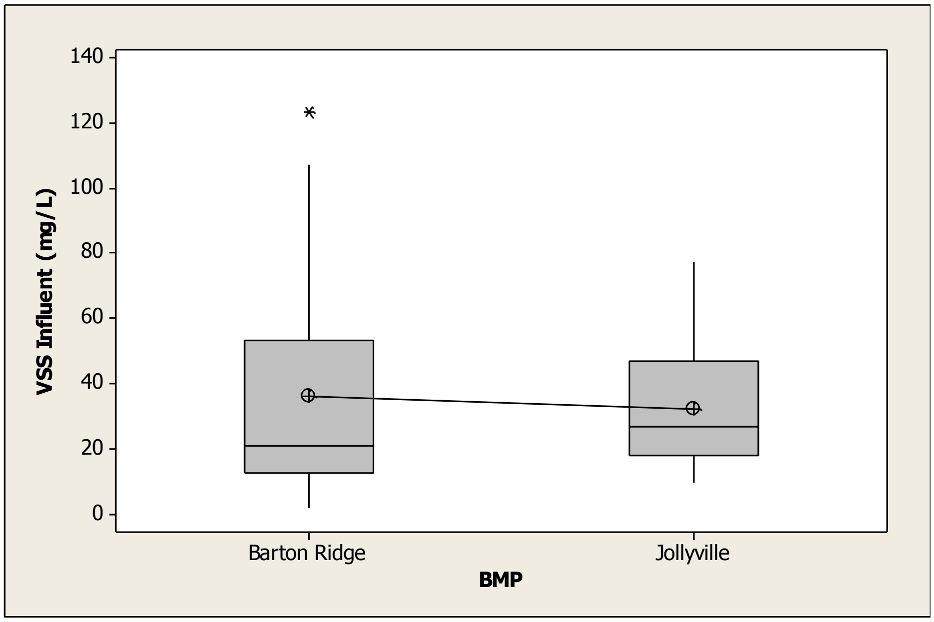

Figure 16 Boxplot of Influent VSS concentrations

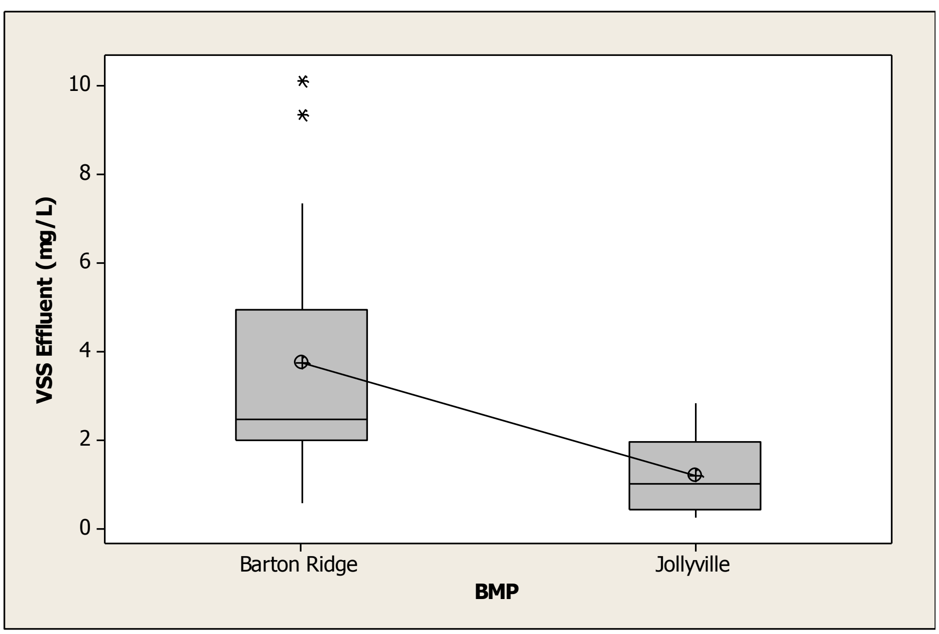

Figure 17 Boxplot of Effluent VSS concentrations

Table 6 summarizes the average concentrations observed based on paired data. Performance of the two systems is similar and both exhibit statistically significant removal.

Table 6 VSS Concentrations for Individual Sites based on Paired Data

Site	EMC in	EMC out	Efficiency Ratio	Wilcoxon SRT
Barton Ridge	32	3.6	89	0.001
Jollyville	30	1.2	96	0.004
All Sites	31.5	2.5	92	<0.000

Figure 18 presents the "relationship" between influent and effluent concentrations, which is not statistically significant (p = 0.214). This is a difficult figure to interpret since the points for the two sand filters seem to fall in distinctly different areas, making a prediction of the effluent concentration very uncertain.

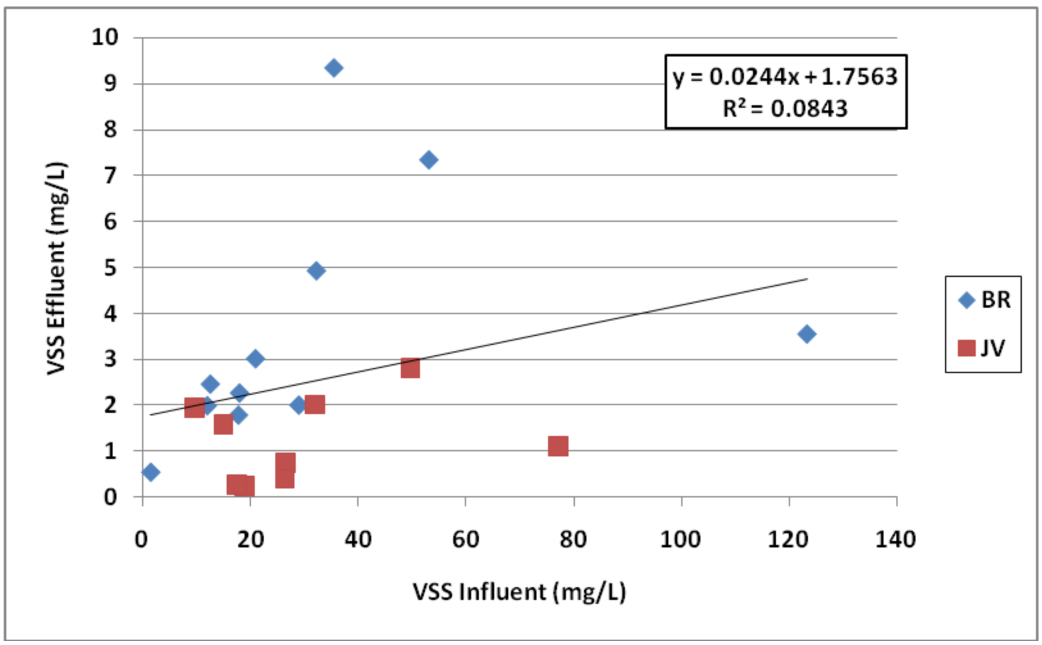

Figure 18 Relationship Between VSS Influent and Effluent Concentrations

Figure 19 presents the time series of VSS concentrations at Jollyville. There is a distinct first flush effect; however, the concentrations are fairly low – normally less than 2 mg/L.

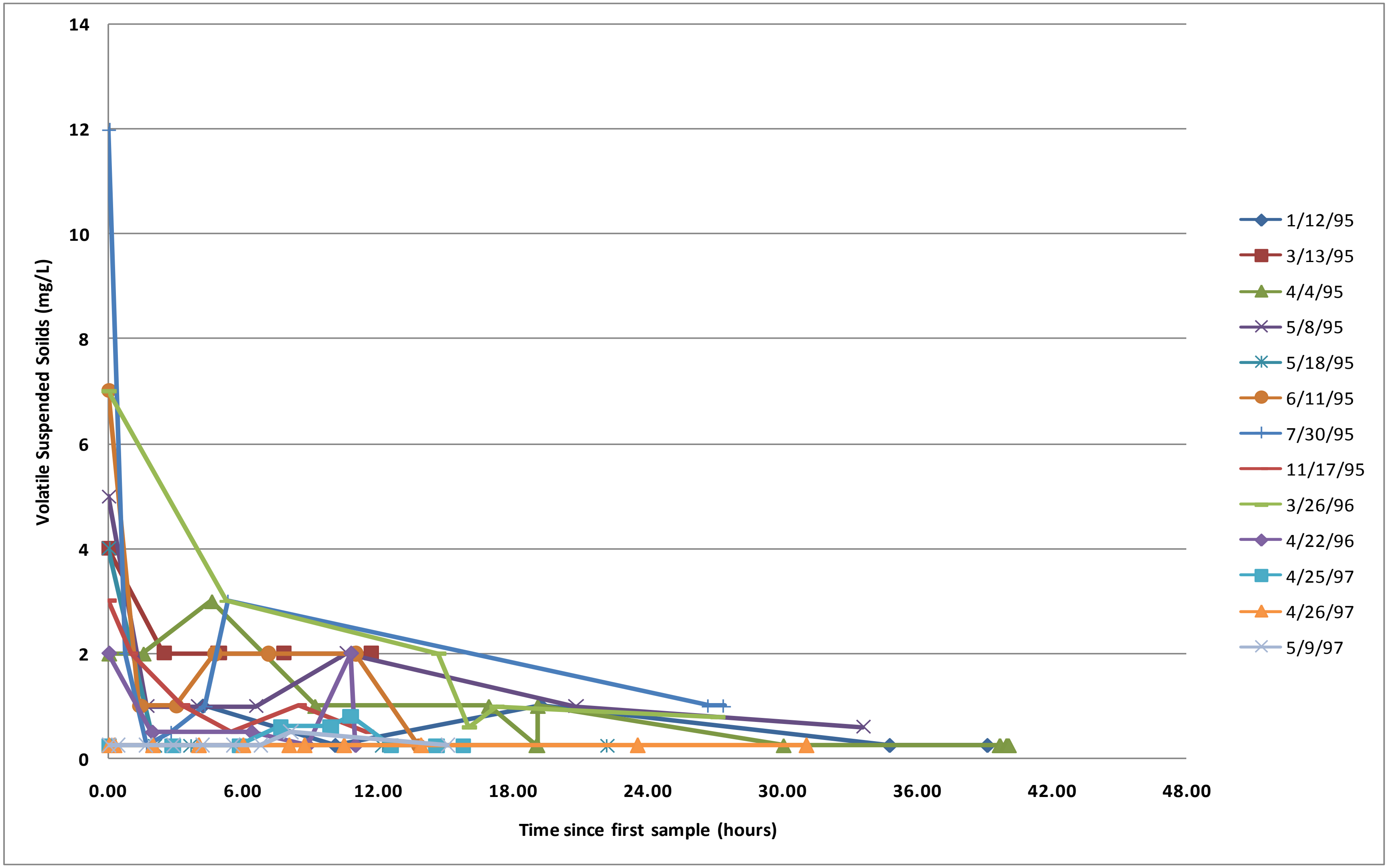

Figure 19 Temporal Pattern of VSS Discharge Concentrations at Jollyville

VSS Conclusions

1. VSS concentrations tend to follow a lognormal distribution.
2. Removal is similar to that observed for TSS and is statistically significant at both sites.
3. VSS discharge concentrations tend to have a first flush pattern, although it is somewhat muted because of the generally low concentrations.

4 Total Phosphorus Performance

The total P data were analyzed to determine whether they fit a normal or lognormal distribution. At most sites there was no clear cut answer with neither distribution being rejected. Figure 20 presents the cumulative probability plots for both the influent and effluent total phosphorus concentrations based on the pooled and paired data. The effluent distribution is significantly different from the lognormal distribution, but this may be the result of detection limited values at the low end

Table 7 Statistical Distribution of Total Phosphorus Data for Each Site

	Barton Mall	Barton Ridge	Brodie Oaks	Highwood	Jollyville	All sites
Influent	Normal/Lognormal	Lognormal	Normal/Lognormal	?	Normal/Lognormal	Lognormal
Effluent	Normal	Lognormal	Normal/Lognormal	?	Normal/Lognormal	?

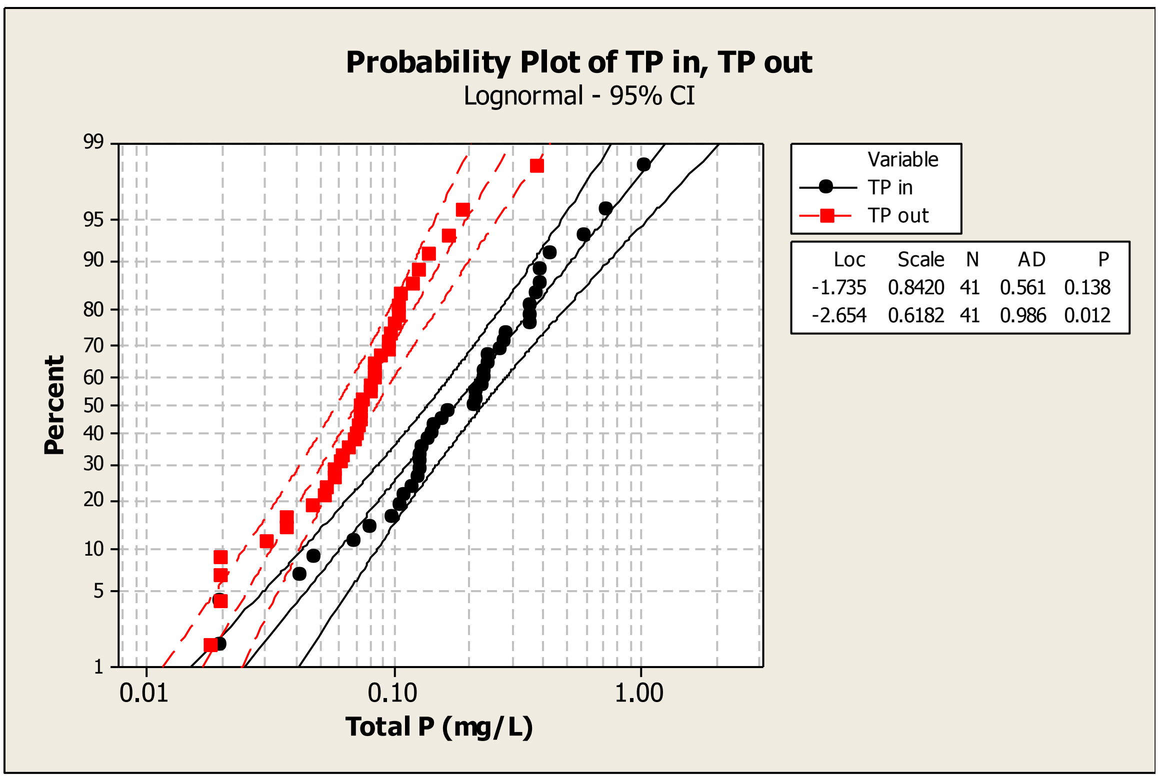

Figure 20 Probability Plots of Total P Influent and Effluent

Much of the phosphorus in runoff is associated with particulate material (50-80%); consequently, one would expect that the removal mechanism (particle retention) for the majority of phosphorus in sand filters would be similar to that observed for TSS. The influent and effluent concentrations at the five sites are compared in Figure 21 and Figure 22 respectively. The influent concentrations are significantly different ($p < 0.000$); however, discharge concentrations are not significantly different ($p = 0.378$), which is similar to what was observed for TSS.

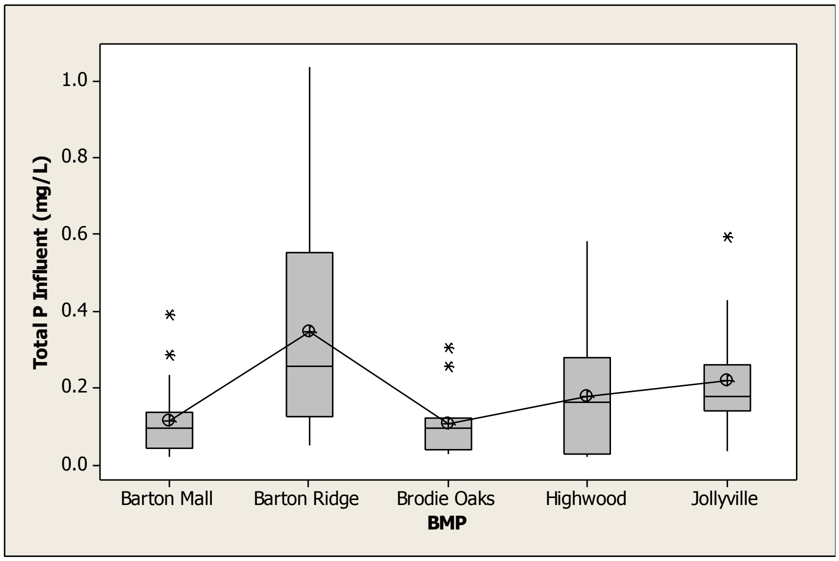

Figure 21 Boxplot of Total P Influent Concentrations

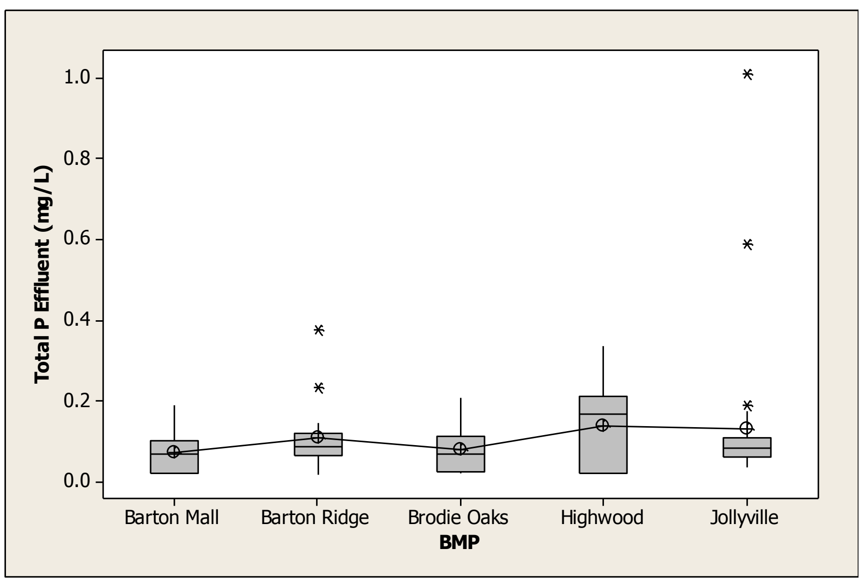

Figure 22 Boxplot of Total P Effluent Concentrations

Concentrations for the individual sites are presented in Table 8. There is substantially variability in the efficiency ratio; however, it is clearly related to influent concentration. The two sites with apparent negative removal (although not statistically significant) both have influent concentrations that are similar to the effluent concentrations at all the other sites.

Table 8 Total Phosphorus Concentrations for Individual Sites based on Paired Data

Site	EMC in	EMC out	Efficiency Ratio	Paired t-test
Barton Mall	0.15	0.08	47	0.002
Barton Ridge	0.32	0.10	69	0.022
Brodie Oaks	0.07	0.08	-14	1.000
Highwood	0.11	0.12	-9	0.508
Jollyville	0.24	0.08	67	<0.000
All Sites	0.22	0.08	61	<0.000

The relationship between influent and effluent phosphorus concentration is presented in Figure 23 for the pooled data. Of particular interest is the elevated discharge concentrations at Highwood compared to the other locations based on paired data. (Non - paired data include many storms with low discharge concentrations, which results in the effluent concentrations not being significantly different on average than the other sites.) Highwood is a manicured vegetated area within an apartment complex, so it would not be surprising if the landscape management company applied fertilizer. There is no particular trend of concentration with time; however, many of the higher readings occurred for storms in the fall of 1986.

The regression line shown for these data in Figure 23 do not include the Highwood values. The regression line is much steeper than that observed for TSS, which means that removal is less. This result is likely related to the fact that a substantial amount of the phosphorus is dissolved, but another factor could be that the P is more associated with the finest clay particles that are not removed as effectively. The regression analysis was also performed for the individual sites and was only statistically significant at three of the facilities: Highwood, Barton Ridge, and Barton Creek Square Mall. The plots for these locations are presented in Figure 24, Figure 25, and Figure 26, respectively.

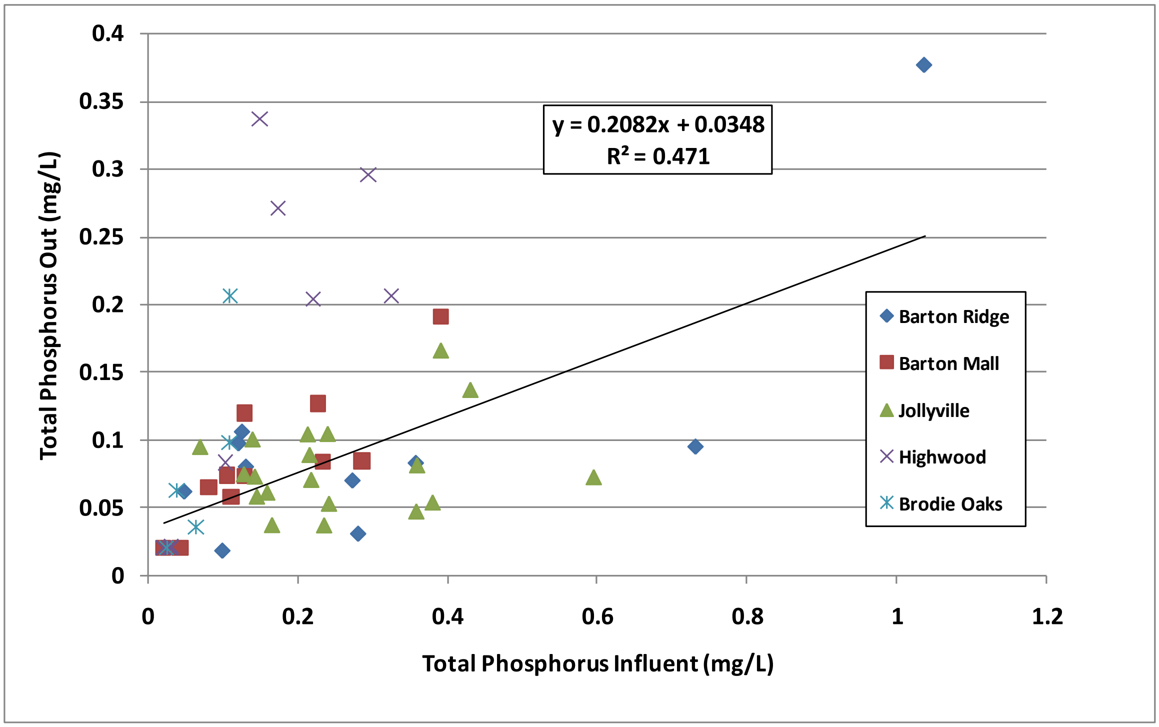

Figure 23 Relationship between P Influent and Effluent Concentrations All Sites

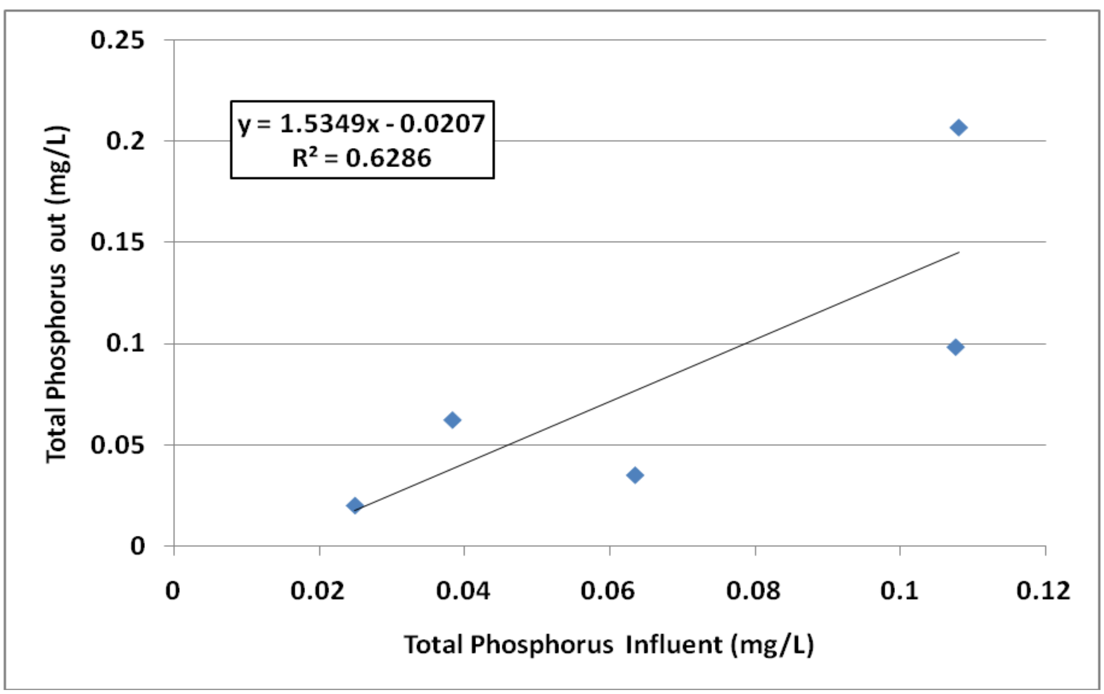

Figure 24 Relationship between P Influent and Effluent Concentrations for Highwood

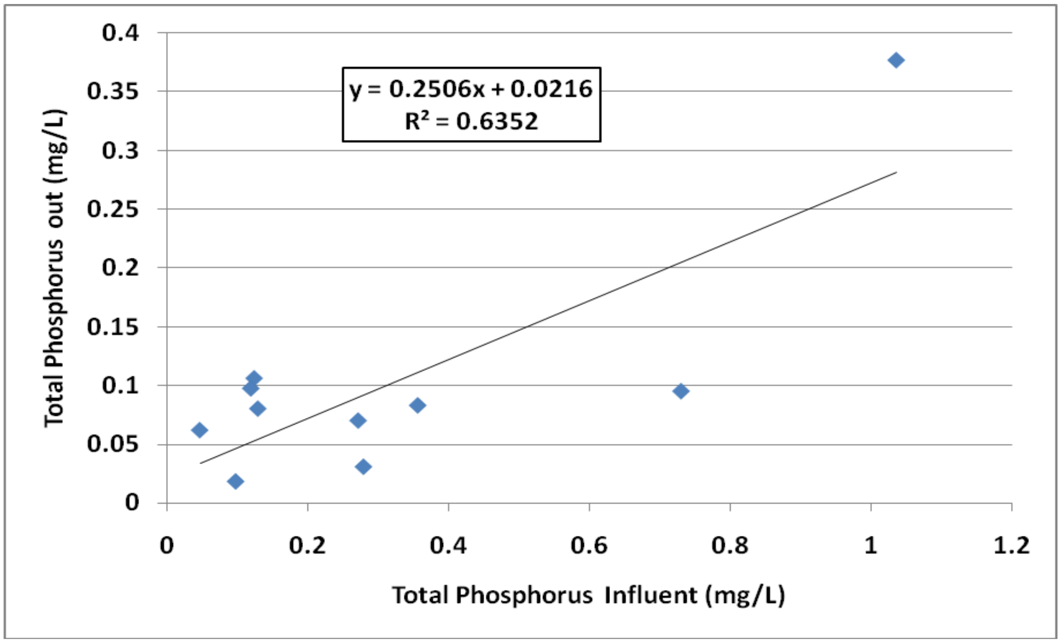

Figure 25 Relationship between P Influent and Effluent Concentrations for Barton Ridge

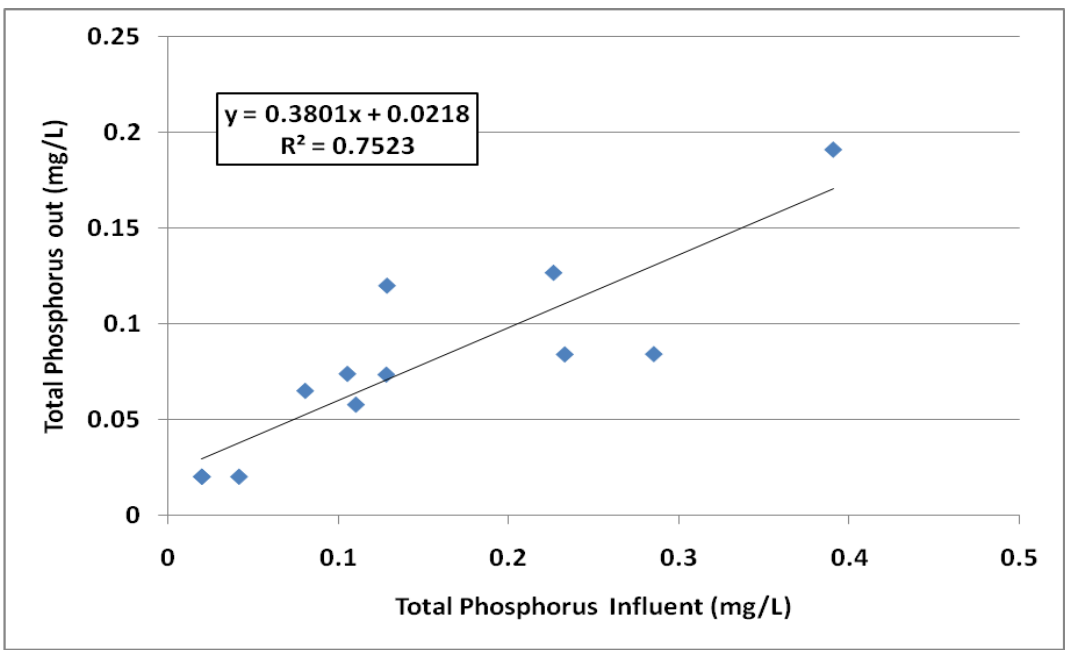

Figure 26 Relationship between P Influent and Effluent Concentrations for Barton Mall

Figure 27 presents the temporal trend of total P concentrations in individual events at Jollyville, with time zero set at the time the first sample of the event was collected. The trend is very similar to that observed for TSS, with an obvious first flush type of pattern, but relatively constant concentrations of less than 0.10 mg/L beyond that.

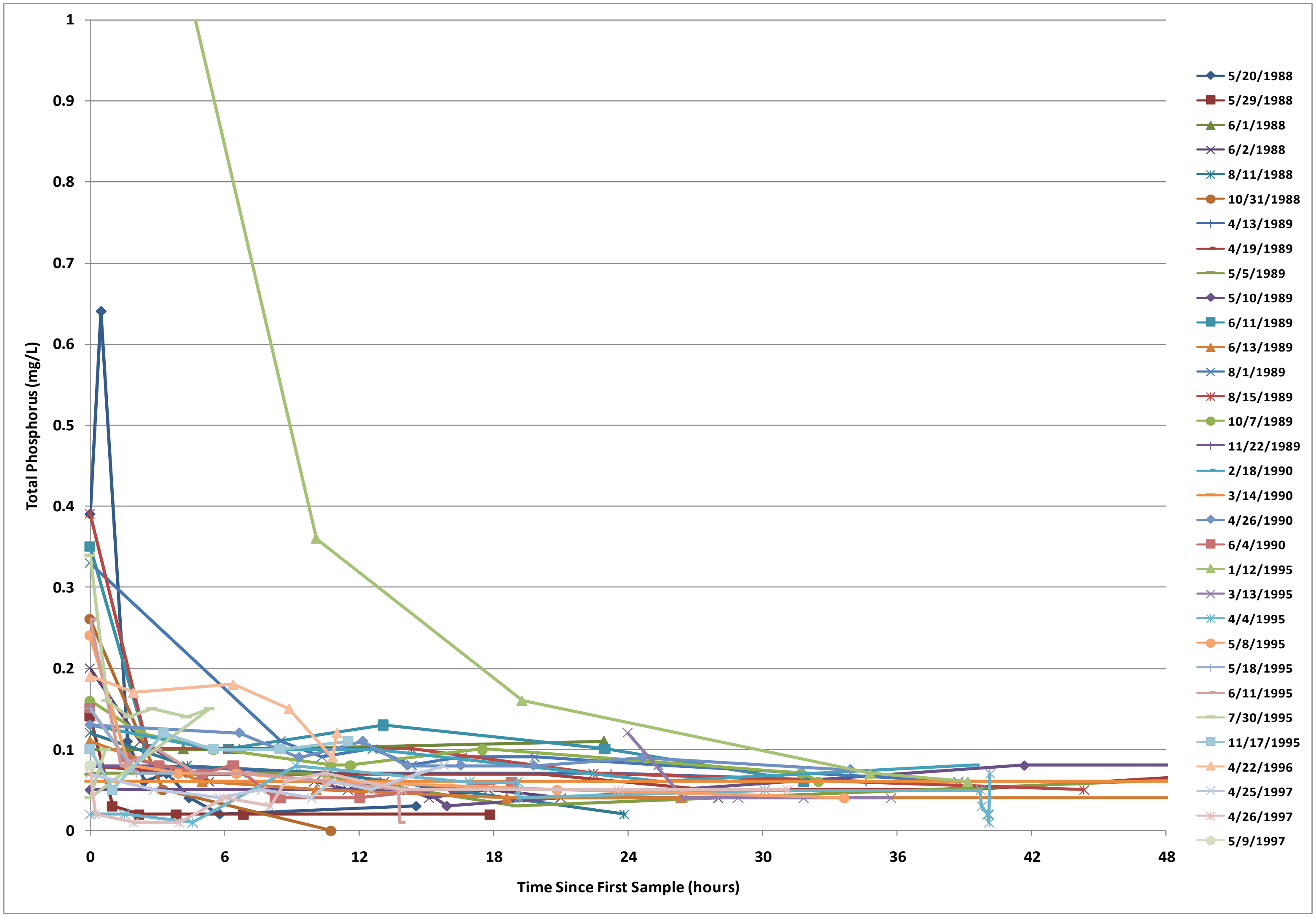

Figure 27 Jollyville Total Phosphorus Time Series Discharge Concentration

Since a substantial amount of phosphorus is in the dissolved form, it is possible that removal might be affected by residence time. Figure 28 presents the relationship between removal efficiency and hydraulic residence time for the Jollyville data. There is no statistically significant relationship between either removal efficiency or discharge concentration and HRT.

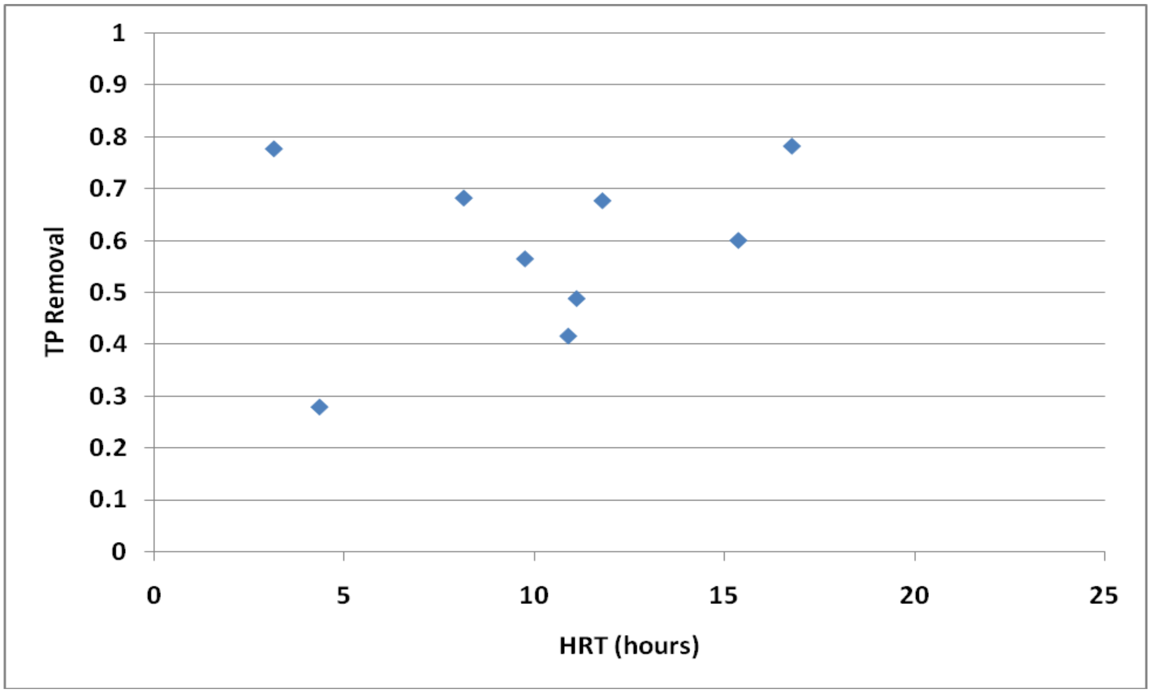

Figure 28 Relationship between HRT and Total P Removal (Jollyville)

Total Phosphorus Conclusions:

1. The distribution of the data is not clearly either normal or lognormal.
2. Effluent concentrations at the five sites are not statistically different, indicating that facility design has little impact on performance.
3. The temporal pattern of discharge concentrations exhibits a first flush effect similar to that observed for TSS.
4. The single vegetated site tends to have higher discharge concentrations, suggesting that fertilizer has been applied by landscape crews.
5. The relationship between influent and effluent phosphorus concentrations is much steeper that that observed for TSS indicating less removal, probably the result of a substantial dissolved fraction.

6. Removal efficiency and discharge concentrations are independent of HRT based on the range of data available currently.

5 Dissolved Phosphorus Performance

Information on dissolved phosphorus is limited to two sites, Barton Ridge and Jollyville. The Jollyville data is from the more recent monitoring conducted in the late 90's. An analysis was performed to determine the statistical distribution of the data. Results of this analysis are presented in Table 9 and Figure 29. Individually the dissolved phosphorus data has no clear distribution, mostly due to the small sample size; however, when the data are pooled they clearly fit a lognormal distribution.

Table 9 Statistical Distribution of Dissolved Phosphorus Data for Each Site

	Barton Ridge	Jollyville	All sites
Influent	Normal/Lognormal	Normal/Lognormal	Lognormal
Effluent	Normal/Lognormal	Normal/Lognormal	Lognormal

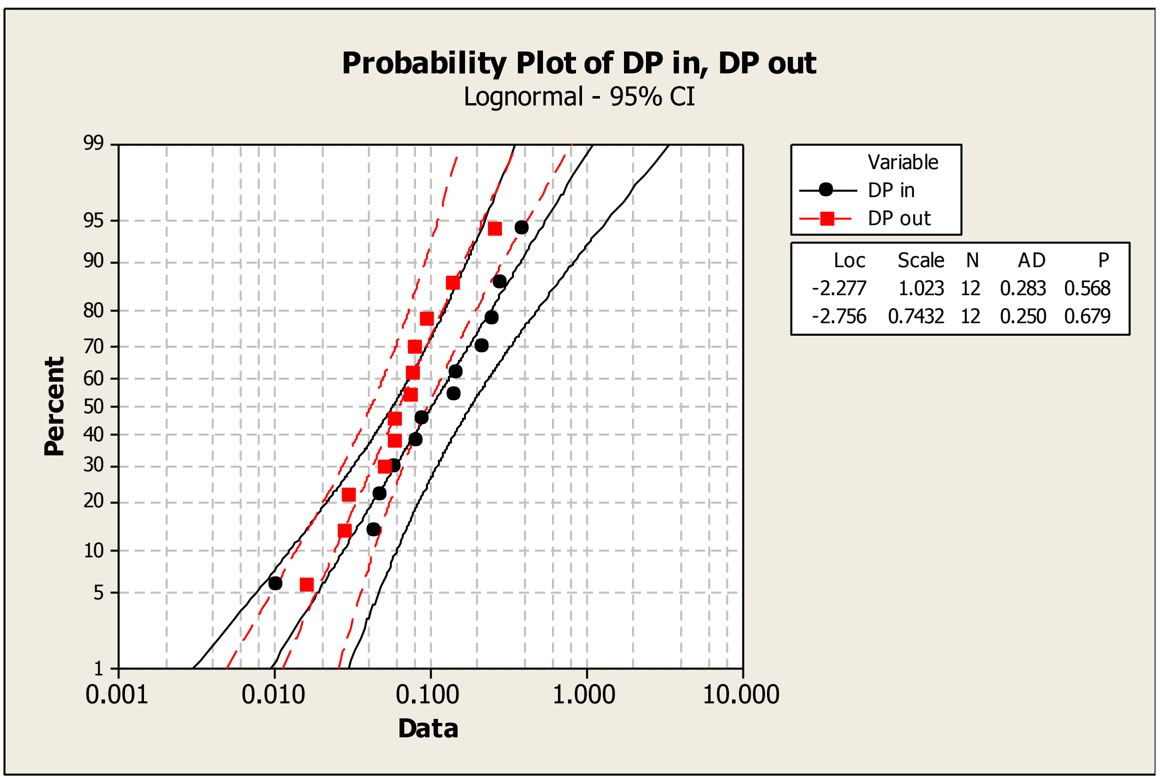

Figure 29 Probability Plots of Dissolved P Influent and Effluent

Boxplots of the influent and effluent concentrations are presented in Figure 30 and Figure 31. ANOVA indicates that neither the influent (p = 0.393) nor the effluent (p = 0.576) are significantly different at the two sites.

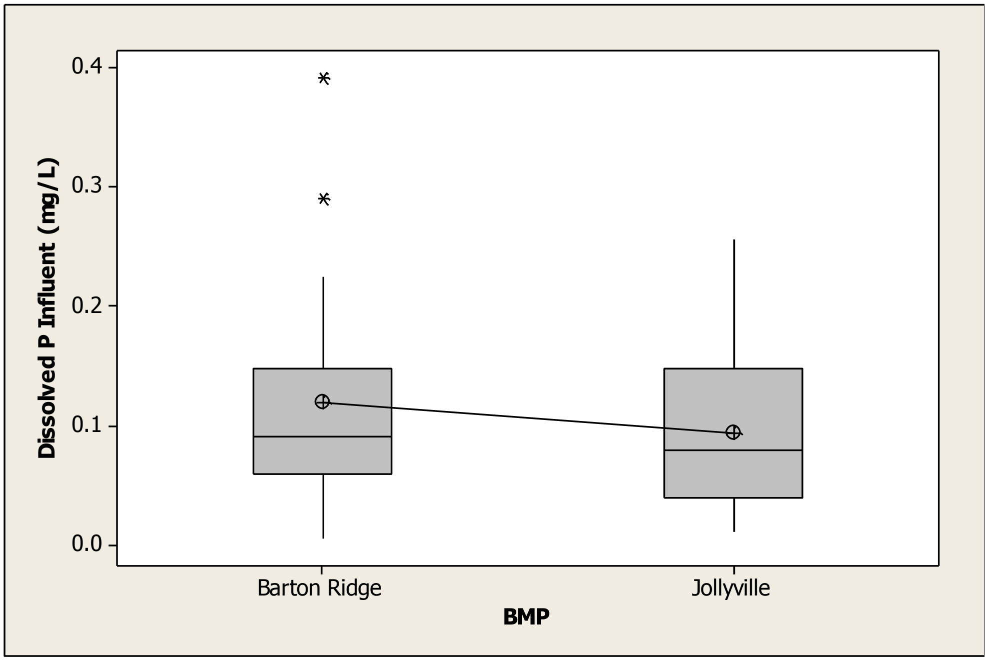

Figure 30 Boxplot of Dissolved P Influent Concentrations

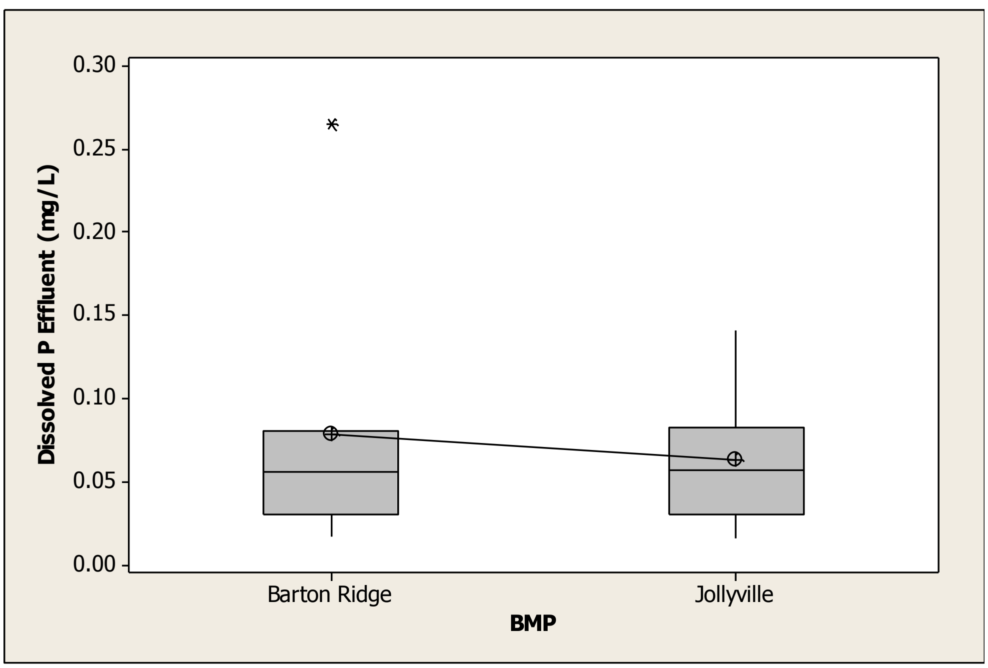

Figure 31 Boxplot of Dissolved P Effluent Concentrations

Average influent and effluent concentrations for each of the sites is presented in Table 10. The data indicate significant removal at each site. The efficiency ratio is less for Jollyville, but this appears to be primarily the result of the relatively low influent concentrations.

Table 10 Dissolved P Concentrations for Individual Sites based on Paired Data

Site	EMC in	EMC out	Efficiency Ratio	Wilcoxon SRT
Barton Ridge	0.22	0.11	52	0.625
Jollyville	0.11	0.07	39	0.727
All sites	0.15	0.08	45	0.023

Figure 32 presents the relationship between influent and effluent dissolved P concentrations. There is a relatively strong correlation evident and substantial removal is indicated, which suggests that adsorption or precipitation is occurring. The regression is not significant when the sites are analyzed individually.

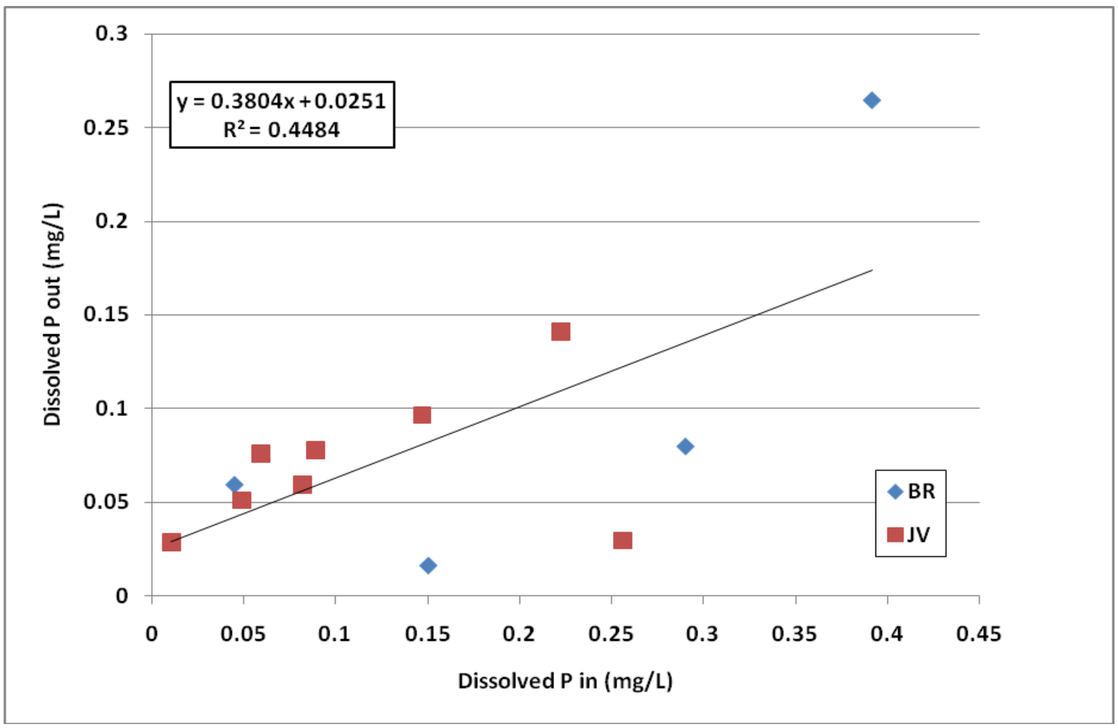

Figure 32 Relationship between Dissolved P Influent and Effluent Concentrations

Figure 33 presents the temporal trend of dissolved P concentrations in individual events at Jollyville, with time zero set at the time the first sample of the event was collected. The trend is in contrast to that of total P and TSS, with no evident first flush. The data also tend to bounce around with samples collected only minutes apart having substantially different concentrations (e.g., event on 4/4/95). This suggests that much of the variability evidenced in the figure may be due to laboratory issues and the fact that many of the measurements are close to the detection limit.

An attempt was made to determine whether the residence time, contact time, or some other variable could explain differences in performance. Unfortunately, there are substantial mass balance errors in the runoff volumes that preclude making this analysis. Table 11 presents the magnitude of the effluent volume to the influent volume for events with dissolved P data, which demonstrate the inconsistency in the measured volumes.

Table 11 Ratio of Effluent/Influent Volume for Events with Dissolved P Data

Jollyville Event	**Volume Ratio**	**Barton Ridge Event**	**Volume Ratio**
6-April	2.3	31-Aug	0.14
11-Jun	0.75	2-Nov	3.45
30-Jul	0.93	11-Jun	0.31
17-Nov	1.36	20-Sep	0.84
26-Mar	2.8		
25-Apr	0.55		
26-Apr	0.43		
9-May	0.32		

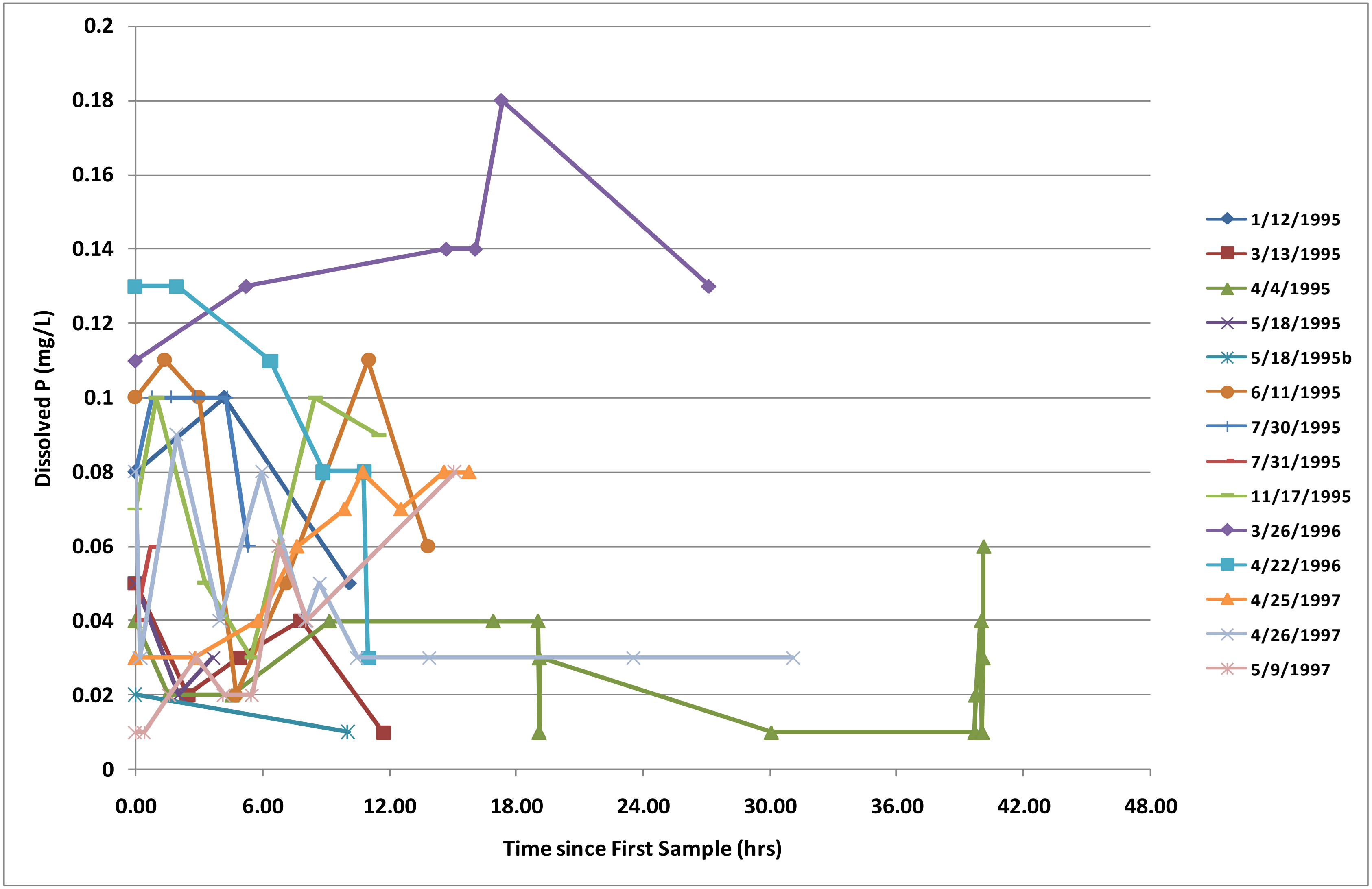

Figure 33 Jollyville Dissolved Phosphorus Time Series Discharge Concentration

Dissolved Phosphorus Conclusions:

1. Effluent concentrations at the two sites are not statistically different, indicating that facility design has little impact on performance.

2. There is no consistent temporal pattern of discharge concentrations and the variability observed is more likely the result of laboratory lack of accuracy than real changes in concentration.

3. Substantial reductions in the concentrations of dissolved phosphorus are evident; however, poor mass balance between influent and effluent volumes makes analysis of rate based processes infeasible.

4. Both influent and effluent concentrations are lognormally distributed.

6 Total Kjeldahl Nitrogen (TKN) Performance

An important consideration when evaluating the performance of sand filters for nitrogen as well as phosphorus removal is the degree to which the influent samples represent the total loading of nutrients to the filter. Manufacturers of proprietary BMPs have frequently complained that influent samples are biased against the larger, heavier particles that are not effectively captured by automatic samplers. The bias also extends to lighter, larger material that is either too large to enter the sampler intake or which floats on the surface like a substantial amount of litter as well as organic matter. On the other hand, only the smallest material can be transported through the filter media, so the effluent sample general is an accurate representation of the overall water quality discharged.

A substantial amount of organic matter, including leaves and grass clippings, are commonly transported in stormwater; however, they are rarely present in stormwater samples or would probably be ignored during laboratory analysis. In addition, many of the facilities are located in landscaped areas with trees in the vicinity. It would be expected that a substantial amount of leaves would be deposited directly in the filtration system during leaf drop (fall for most trees except live oaks). Currently, the Jollyville sand filter has almost a foot of this decaying organic matter resting on the surface of the filter media. This organic material will eventually breakdown and some portion will be nitrified, driving up the total load of nitrate leached from the filter. Consequently, the removal of TKN, nitrate, and possibly phosphorus is almost certainly underestimated.

The monitoring data were analyzed initially to determine their distribution and the results are presented in Table 12. Data from many of the sampling locations were not clearly either normally or lognormally distributed.

Table 12 Statistical Distribution of TKN Data for Each Site

	Barton Mall	Barton Ridge	Brodie Oaks	Highwood	Jollyville	All sites
Influent	Normal/lognormal	Normal/lognormal	Normal/lognormal	Normal/lognormal	Lognormal	?
Effluent	lognormal	lognormal	Normal/lognormal	Normal/lognormal	Lognormal	Lognormal

Figure 34 presents the cumulative probability plot of TKN influent and effluent concentrations using paired data from all the sites. The distributions are distinctly different from each other and the influent distribution is also significantly different from the lognormal distribution.

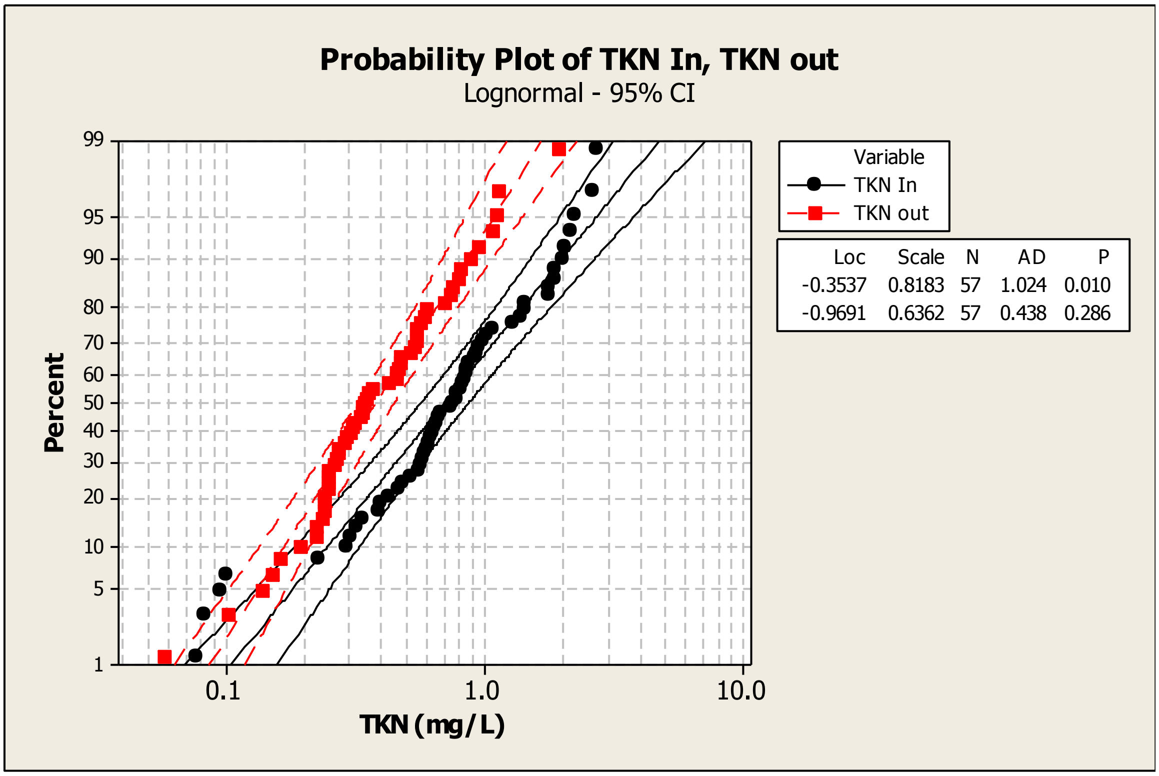

Figure 34 Probability Plot of TKN Influent and Effluent

Boxplots of influent and effluent TKN concentrations are presented in Figure 35 and Figure 36. Differences in concentrations are significant for both the influent ($p < 0.000$) and effluent ($p = 0.023$), which is due to the elevated concentrations at Barton Ridge. However, when effluent concentrations are plotted against influents, the Barton Ridge data does not appear to be substantially higher (Figure 37). In fact, ANOVA indicates that the differences are not significant ($p = 0.410$) when only storms with paired data are used to make the comparison. The likely explanation for the differences in discharge quality is the substantial dissolved component which is not effectively removed by the filter.

Mean influent and effluent concentrations, along with their efficiency ratio and Wilcoxon SRT comparison, are presented in Table 13. Discharge concentrations at all the sites are very similar; however, the statistical tests indicates that the removal at Barton Creek Square Mall and Highwood is not statistically significant. The apparent poor result at Highwood is due to three events where the influent TKN concentration was less than 0.1 mg/L, which is very low in comparison to most events monitored there and at other sites. These three events had negative removals, which resulted in the overall performance appearing worse than the other sites.

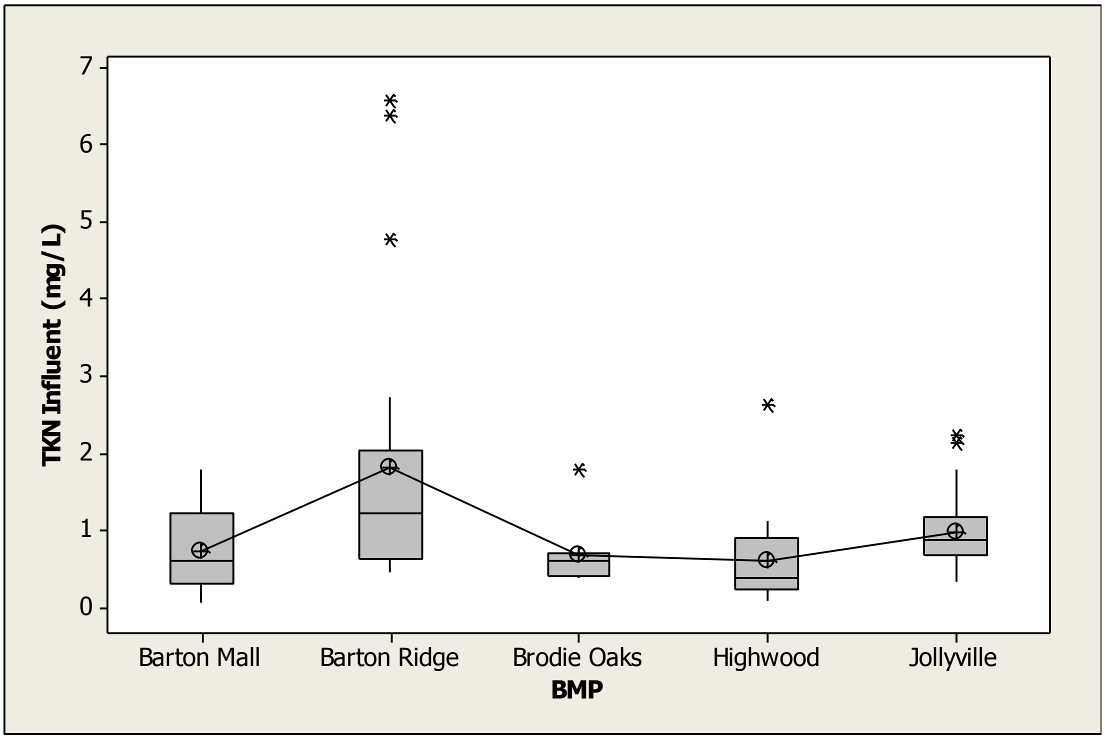

Figure 35 Boxplots of TKN Influent Concentrations

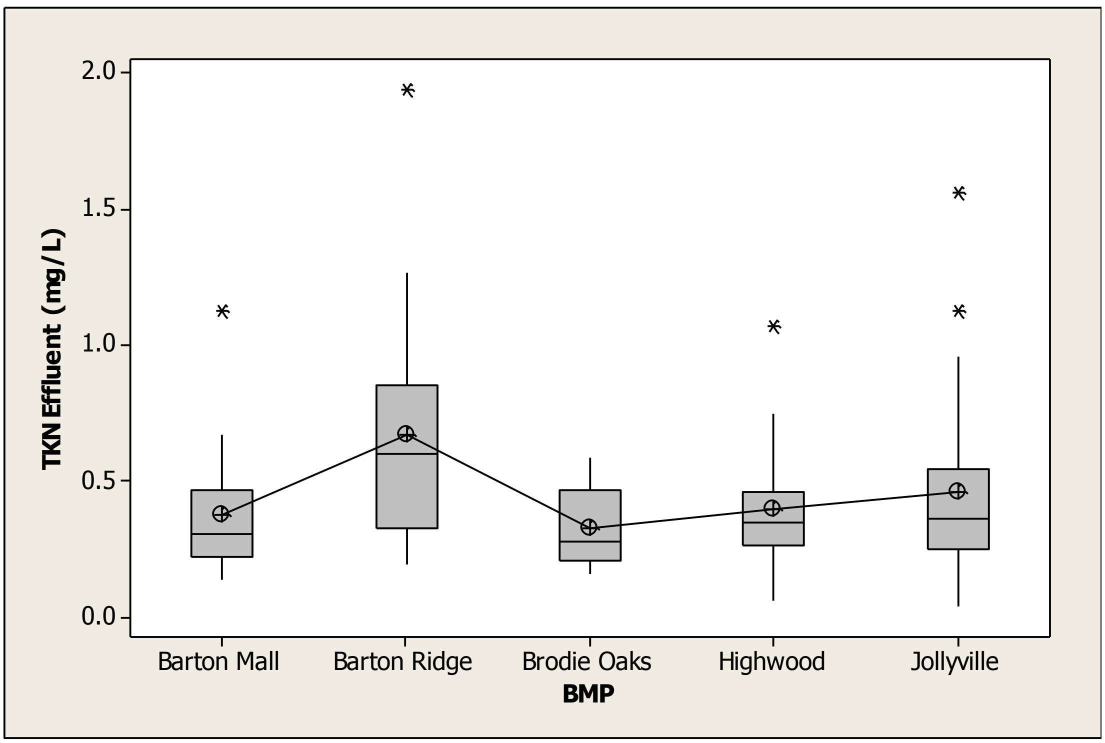

Figure 36 Boxplot of TKN Effluent Concentrations

Table 13 TKN Concentrations for Individual Sites based on Paired Data

Site	EMC in	EMC out	Efficiency Ratio	Wilcoxon SRT
Barton Mall	0.87	0.40	54	0.386
Barton Ridge	1.35	0.64	53	0.001
Brodie Oaks	0.59	0.41	30	0.063
Highwood	0.59	0.43	27	0.344
Jollyville	0.96	0.43	55	<0.000
All Sites	0.92	0.46	50	<0.000

Figure 37 shows a relatively strong correlation between influent and effluent concentrations of TKN at all the sites, which is consistent with the relationships exhibited by many other constituents. When sites are analyzed individually only Barton Ridge and Highwood have statistically significant relationships. These are shown in Figure 38 and Figure 39, respectively.

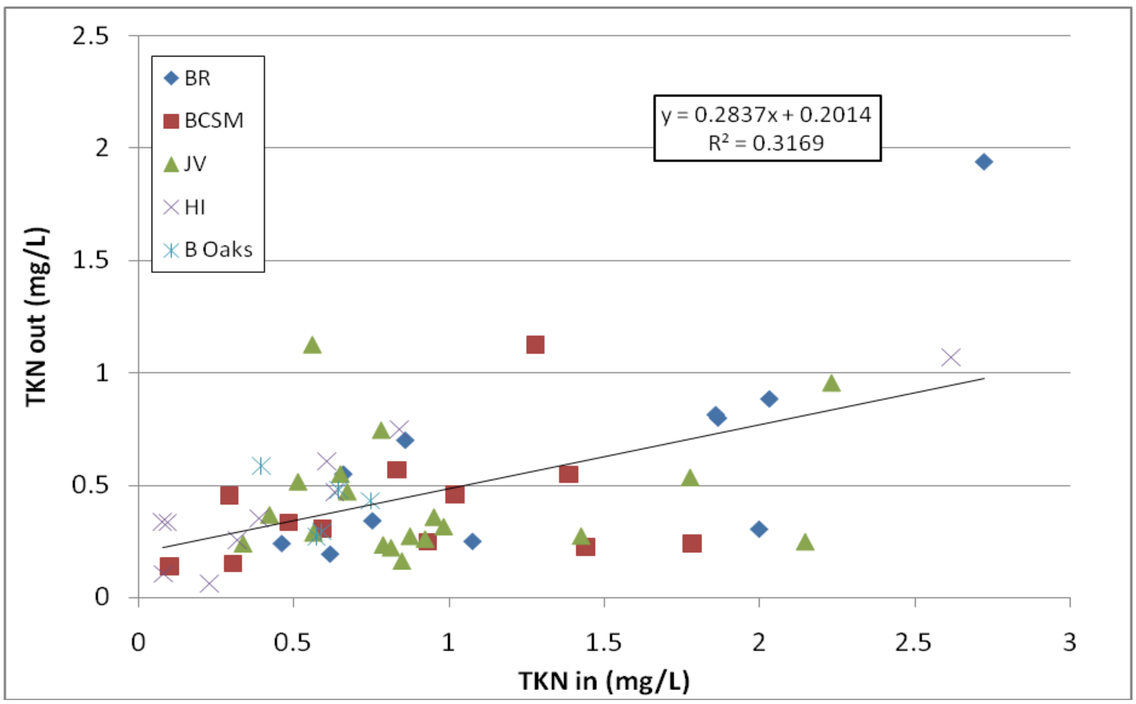

Figure 37 Relationship between Influent and Effluent TKN Concentrations (all sites)

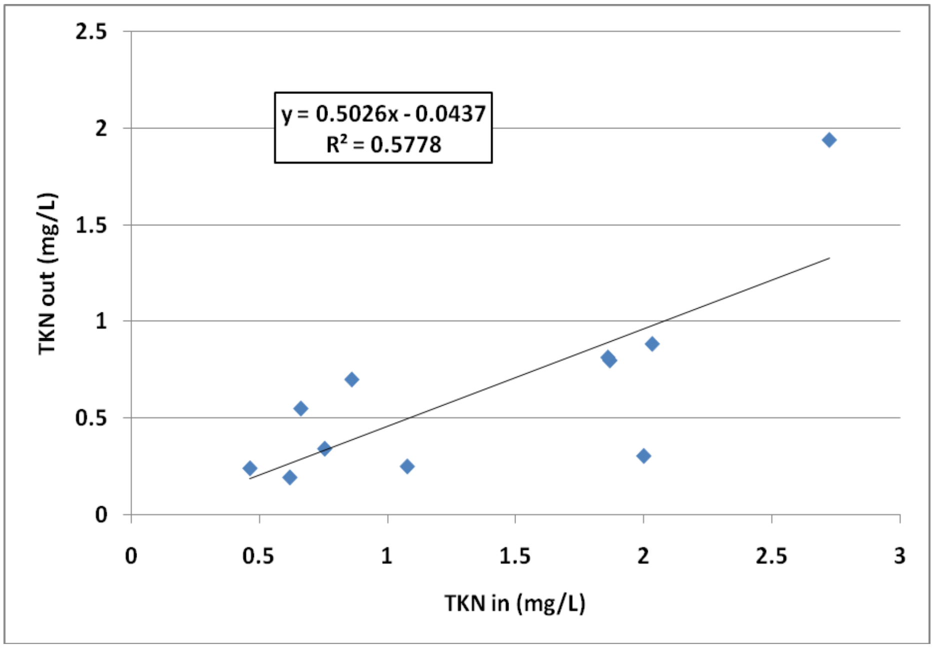

Figure 38 Relationship between Influent and Effluent TKN Concentrations Barton Ridge

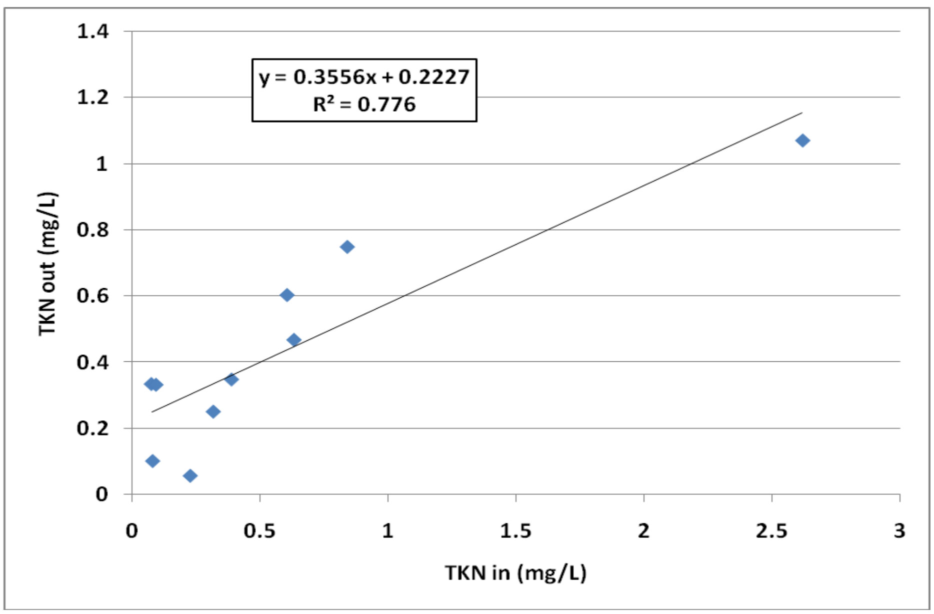

Figure 39 Relationship between Influent and Effluent TKN Concentrations Highwood

Figure 40 presents a time series of the discharge of TKN at Jollyville. Like TSS, there is a strong first flush phenomenon. This is likely also the result of resuspension of material in the underdrain or breakdown of accumulated organic matter during the inter-event period into particles small enough to be transported through the filter media.

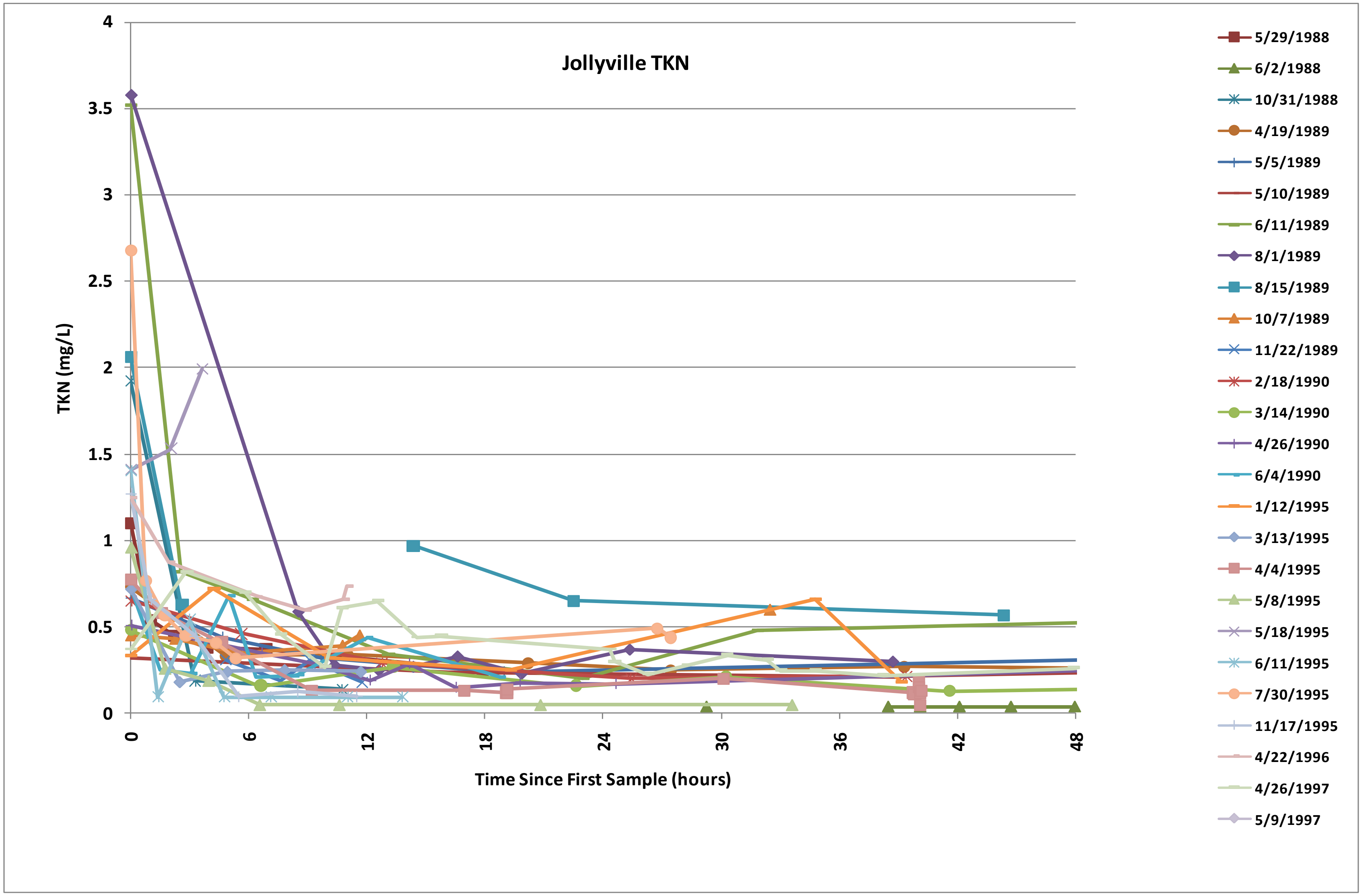

Figure 40 Jollyville TKN Time Series Discharge Concentrations

It has long been observed that sand filters are an exporter of nitrate, which is probably the result of oxidation of ammonia and organic nitrogen. Consequently, it would not be unexpected to find that lower TKN concentrations would be produced by storms with a longer HRT. Figure 41 presents this relationship for the Jollyville site and the regression equation demonstrates the high correlation between these variables. Unfortunately, the effect is the opposite that one would expect with higher discharge concentrations associated with longer hydraulic residence times. Therefore this pattern is more likely related to factors other than processes that occur on and within the filter.

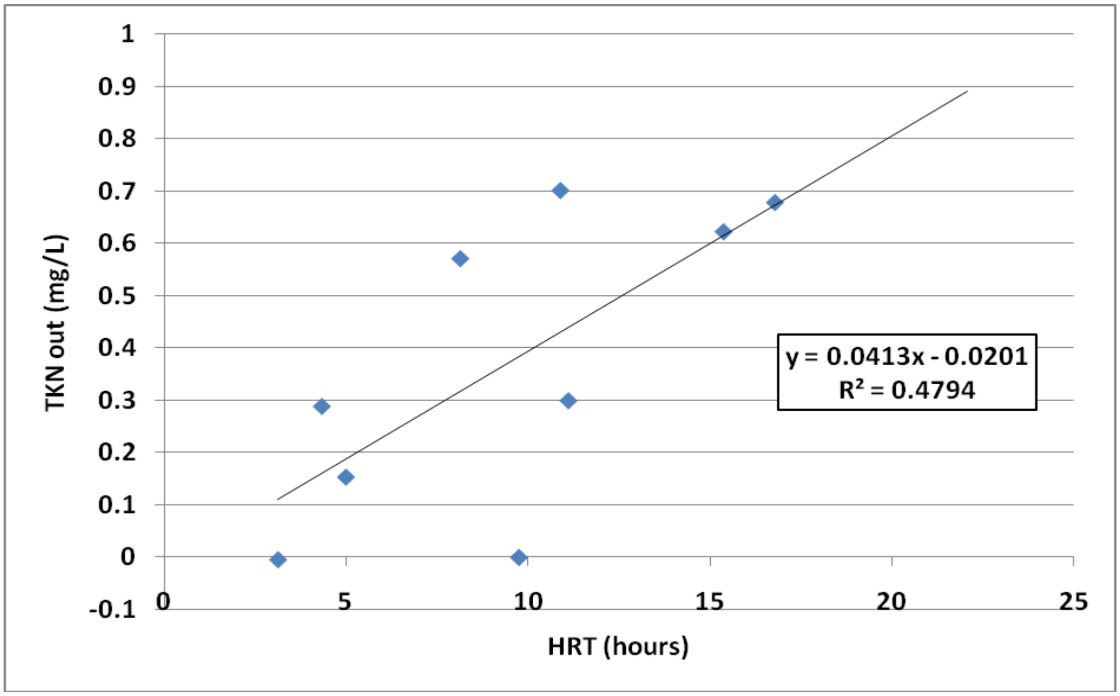

Figure 41 Relationship between HRT and TKN Removal (Jollyville)

A regression analysis was also performed on the Jollyville data to determine if the discharge concentration could be predicted based on influent concentration and HRT. The regression was statistically significant ($p = 0.013$), with both influent concentration ($p = 0.005$) and HRT ($p = 0.052$) being significant. The R^2 for this relationship was 0.75, which means that virtually all the variability in the discharge concentrations are explained by just these two variables. Note that in the multiple regression the coefficient for HRT is negative which indicates that longer residence times do reduce the TKN discharge, all other factors being equal.

$$\text{TKN out} = 0.343 - 0.0225\ \text{HRT} + 0.363\ \text{TKN in}$$

Conclusions for TKN

1. Performance of all the facilities for TKN removal is very similar, except that discharge concentrations at Barton Ridge tend to be higher than other sites, which is the result of significantly higher influent concentrations.

2. A first flush phenomenon in the discharge from the filtration systems is also evident for TKN.

3. TKN is one of the few constituents whose removal is correlated with hydraulic residence time; however the effect is only apparent when influent concentration is included in the regression.

7 Nitrate plus Nitrite Performance

Sand and other media filters have been routinely shown to be exporters of nitrate, with effluent concentrations substantially above influent concentrations. As mentioned previously, this may be due in part to unsampled contributions from leaves, grass clippings, and other organic material washed into the basins during storms or otherwise deposited in the filter in the interevent period.

As shown in Table 14, the concentration data at the individual does not have a clear statistical distribution. Figure 42 presents the cumulative probability plot of nitrate influent and effluent concentrations using paired data from all the sites. The distributions are distinctly different from each other and the influent distribution is also significantly different from the lognormal distribution.

Table 14 Statistical Distribution of Nitrate Data for Each Site

	Barton Mall	Barton Ridge	Brodie Oaks	Highwood	Jollyville	All sites
Influent	Normal/ lognormal	Normal/ lognormal	normal	lognormal	?	?
Effluent	Normal/ lognormal	lognormal	lognormal	Normal/ lognormal	?	lognormal

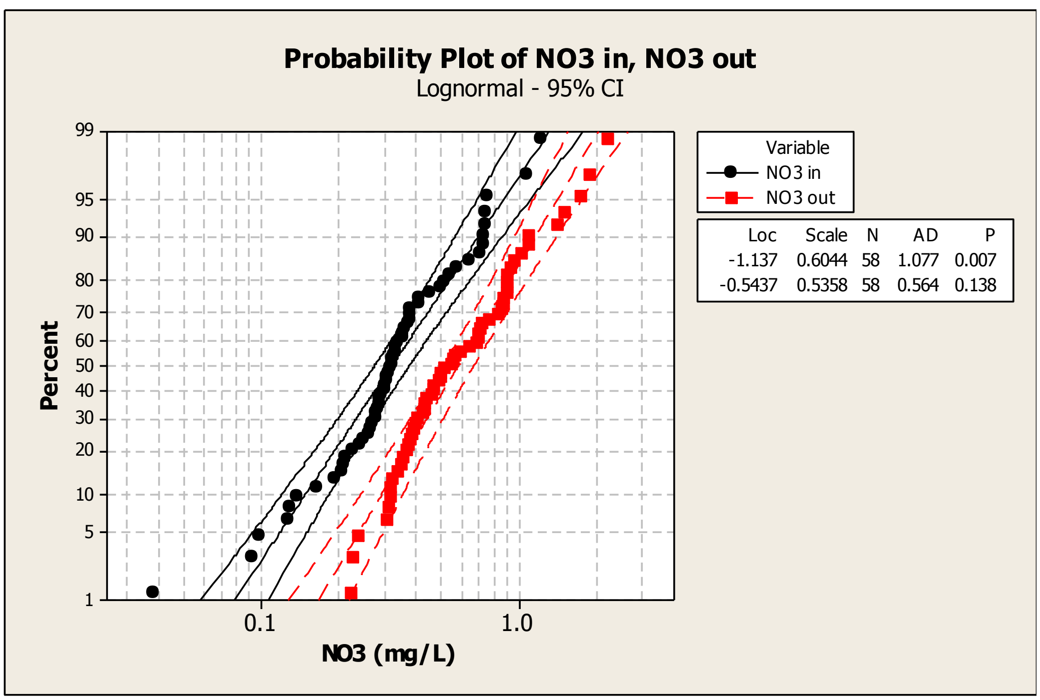

Figure 42 Probability Plots of NO_{2+3} Influent and Effluent Concentrations

Boxplots of NO_{2+3} concentrations indicate that both influent ($p = 0.002$) and effluent ($p = 0.019$) concentrations, Figure 43 and Figure 44 respectively, are significantly different at the five sites. The differences in discharge concentrations are the result of particularly low concentrations observed at Highwood. Excluding that site differences in discharge concentrations are not significant ($p = 0.544$).

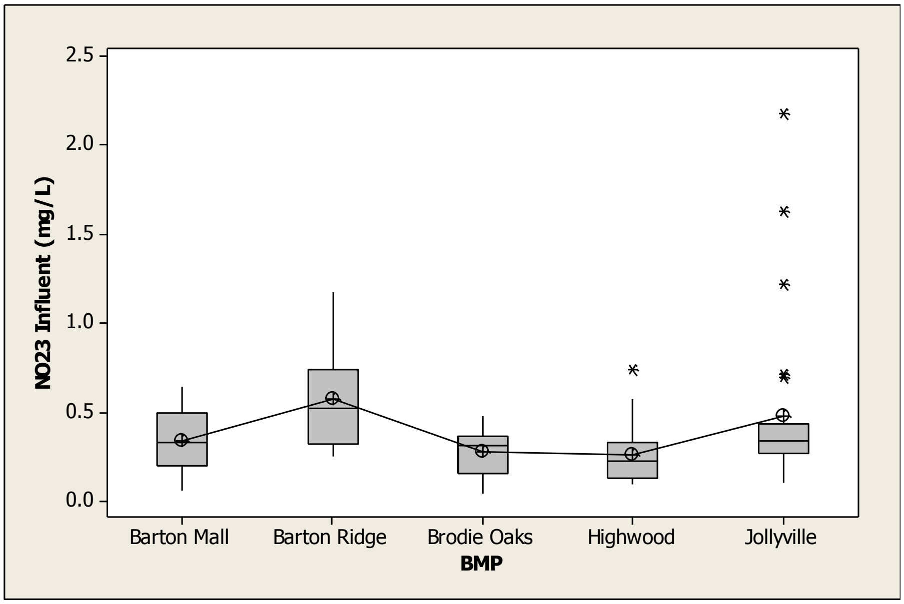

Figure 43 Boxplot of Nitrate + Nitrite Influent Concentrations

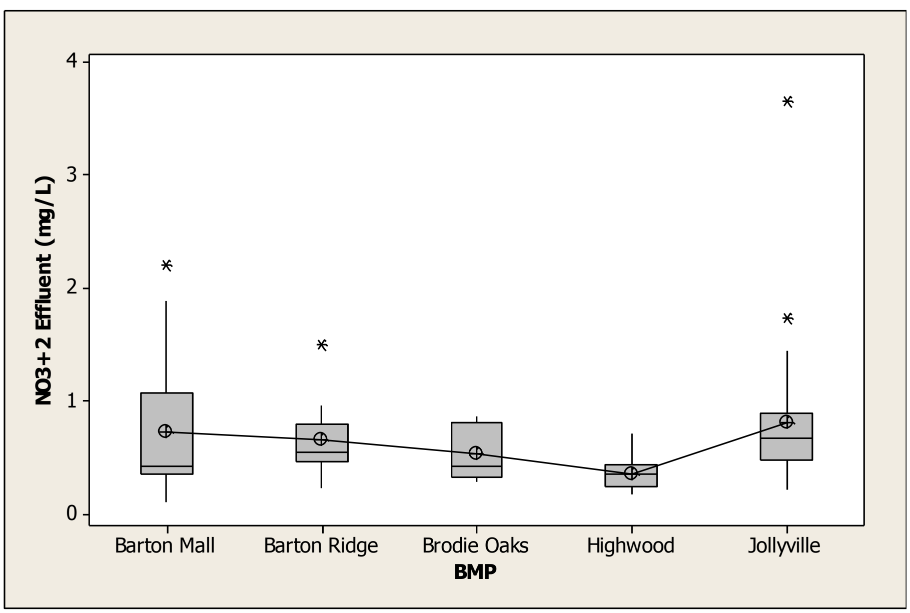

Figure 44 Boxplot of Nitrate + Nitrite Effluent Concentrations

One reason for the low concentrations at Highwood may be the particularly low filtration volume. The filtration component of the system is confined to some 10’s of feet of linear trench, so the volume available for nitrification is very limited compared to the other locations. In addition, the system currently has a bad connection between the overflow outlet and discharge pipe that may allow a substantial amount of the runoff to discharge without passing through the filter media. It is unknown if the same condition existed when the monitoring was conducted.

Like previous studies these data also indicate about a 75% increase in discharge concentrations compared to influent concentrations. Mean EMCs for each of the sites are presented in Table 15.

Table 15 Nitrate Concentrations for Individual Sites based on Paired Data

Site	EMC in	EMC out	Efficiency Ratio	Wilcoxon SRT
Barton Mall	0.37	0.96	-160	0.006
Barton Ridge	0.56	0.68	-21	0.549
Brodie Oaks	0.24	0.48	-100	0.062
Highwood	0.26	0.40	-54	0.006
Jollyville	0.41	0.72	-76	<0.000
All Sites	0.38	0.67	-75	<0.000

Figure 45 presents the relationship between influent and effluent concentrations. The effluent concentrations tend to be higher than the influent, which is a common finding in every sand filter monitoring study. Some of the poorest nitrate removal shown in Figure 45 apparently occurs at Barton Creek Square Mall, which has some of the highest reported discharge concentrations especially in relation to the influent concentration for the event. A closer look reveals that all of these higher discharge concentrations were calculated based on only three samples. As is evident in Figure 49 almost all storms have very elevated NO23 concentrations for the first sample, but within a very brief period of time the concentrations drop dramatically. Because of the few discrete samples from many events at BCSM, these higher concentrations are applied to a much larger volume of runoff than is likely warranted.

For the individual sites, the relationship between influent and effluent concentrations was significant for Barton Ridge Jollyville, and Highwood. The individual regressions for these sites area presented in Figure 46, Figure 47, and Figure 48, respectively.

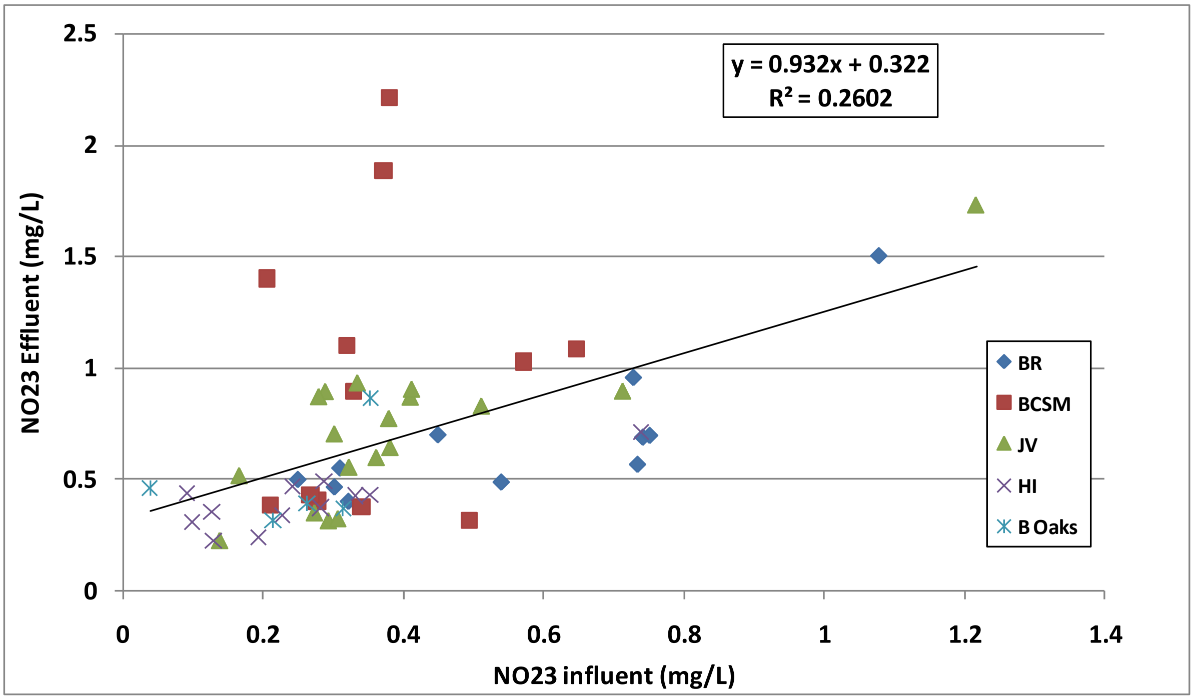

Figure 45 Relationship Between Influent and Effluent NO23 Concentrations (all sites)

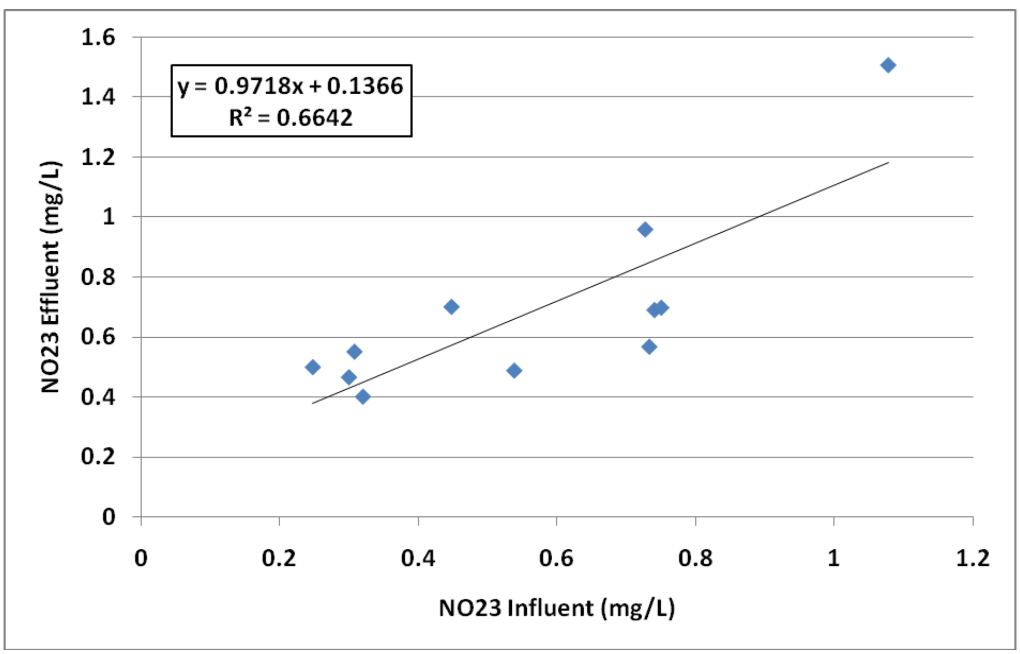

Figure 46 Relationship Between Influent and Effluent NO23 Concentrations Barton Ridge

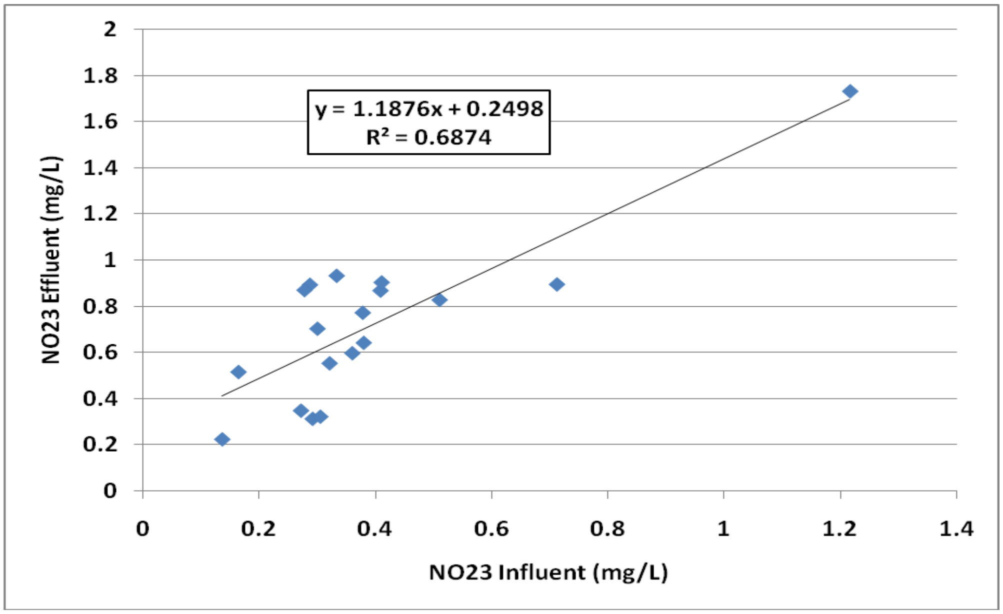

Figure 47 Relationship Between Influent and Effluent NO23 Concentrations Jollyville

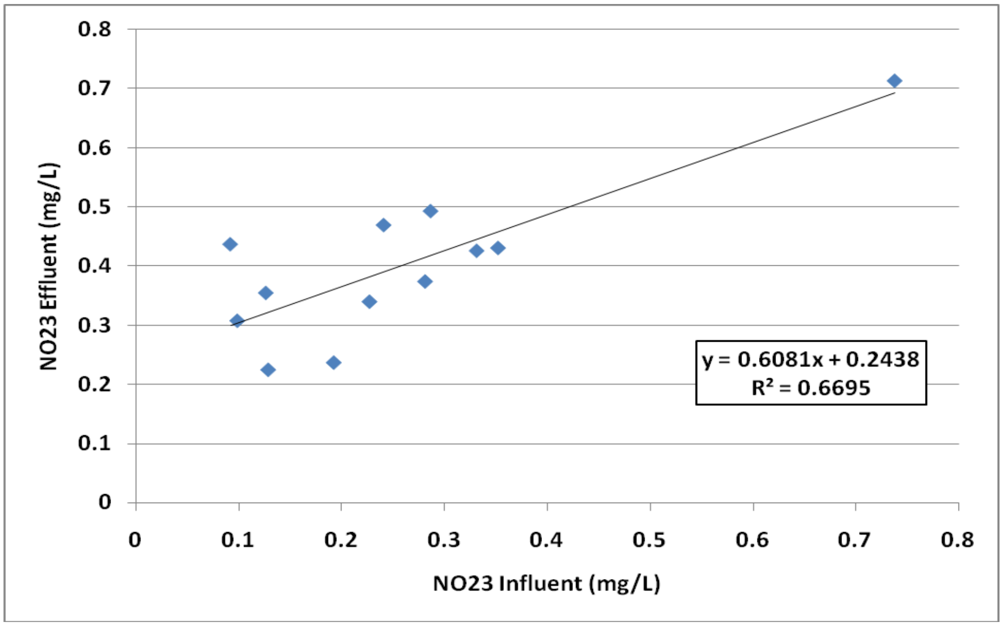

Figure 48 Relationship Between Influent and Effluent NO23 Concentrations Highwood

Like many other constituents there is a pronounced first flush in the filter discharge (Figure 49). Since this is a dissolved constituent, it is likely that the nitrate has formed during the inter-event period from oxidation of organic nitrogen and ammonia (TKN); however, antecedent dry period is not a significant predictor of average discharge concentrations.

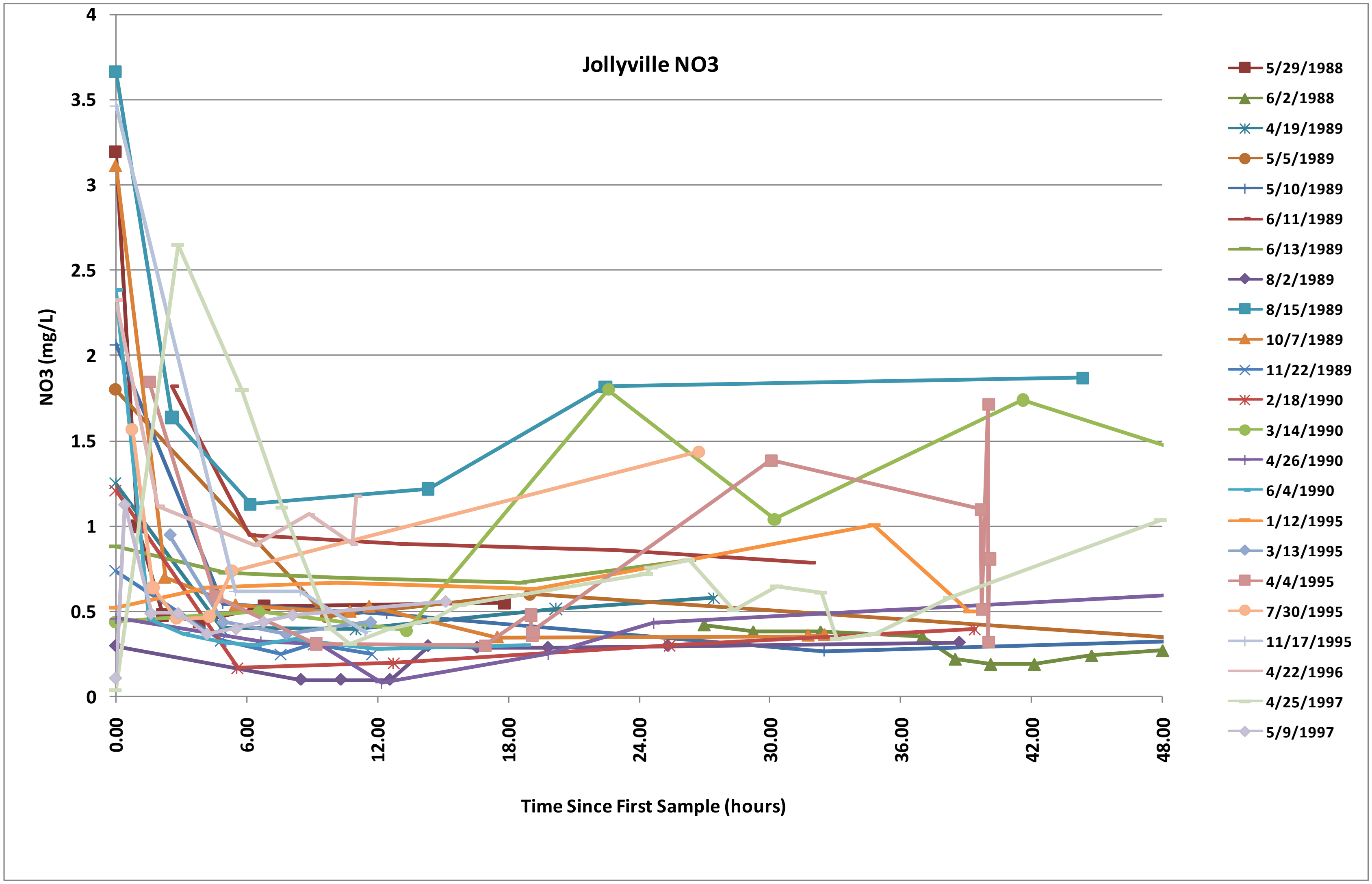

Figure 49 Temporal Trends for NO_{2+3} for Jollyville

On the other hand, antecedent dry period appears to have a substantial impact on the initial concentration observed in the effluent (Figure 50). All the storms with initial discharge concentrations of less than 0.5 mg/L have antecedent dry periods of less than 3 days. This suggests that most nitrification occurs during the inter-event period.

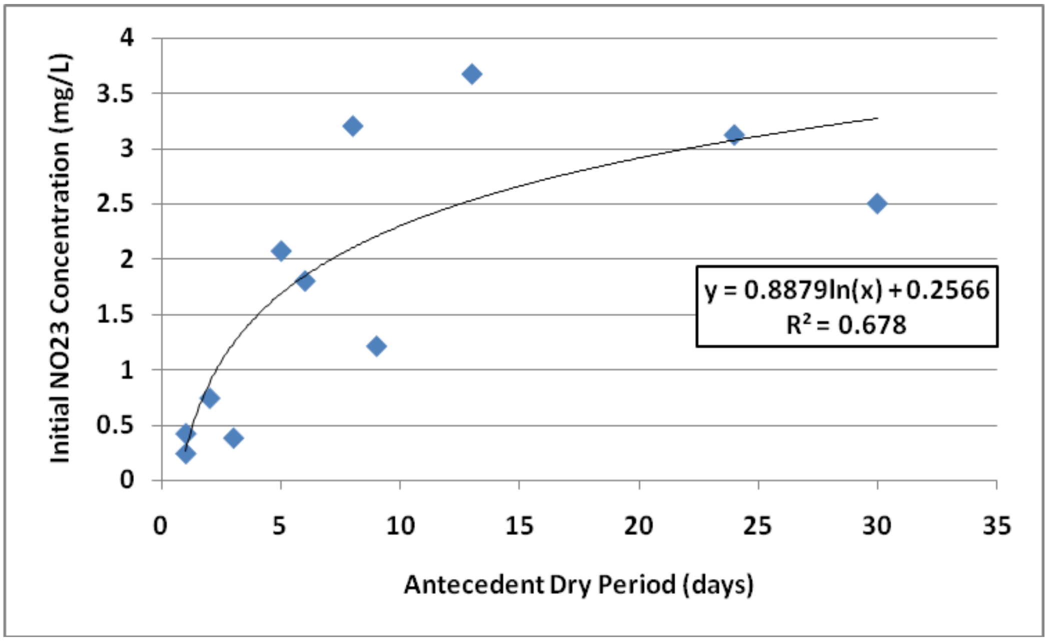

Figure 50 Effect of Antecedent Dry Period on Initial NO23 Concentration

Removal efficiency and discharge concentrations of TKN improve with increased residence time, so one would expect the opposite relationship for nitrate; however, HRT was not a predictor of removal efficiency or effluent concentration, even when normalized for influent concentration ($p = 0.588$).

Nitrate Conclusions

1. Sand filters tend to export nitrate; however, no correlation between TKN removal and nitrate export could be documented.
2. All of the filters except Highwood performed similarly, which may be the result of the very small filter area (and volume) in comparison to the other designs.
3. Nitrate exhibits a pronounced first flush effect that is similar to that observed for other constituents.
4. Initial nitrate concentration increases with increasing antecedent dry period, which suggests that most of the nitrification occurs in the inter-event period.

8 Fecal Coliform Performance

The fecal coliform data at all the sites were analyzed to determine their statistical distribution. Neither the normal or lognormal distributions were dominant as shown in Table 16. Figure 51 presents the cumulative probability plot of fecal coliform influent and effluent concentrations using paired data from all the sites. The distributions show a lot of overlap (marginal differences) and the influent distribution is also significantly different from the lognormal distribution.

Table 16 Statistical Distribution of Fecal Coliform Data for Each Site

	Barton Mall	Barton Ridge	Brodie Oaks	Highwood	Jollyville	All sites
Influent	Lognormal	Lognormal	Lognormal /Normal	?	Lognormal	?
Effluent	Lognormal	Lognormal/Normal	Lognormal	Normal	Lognormal	Lognormal

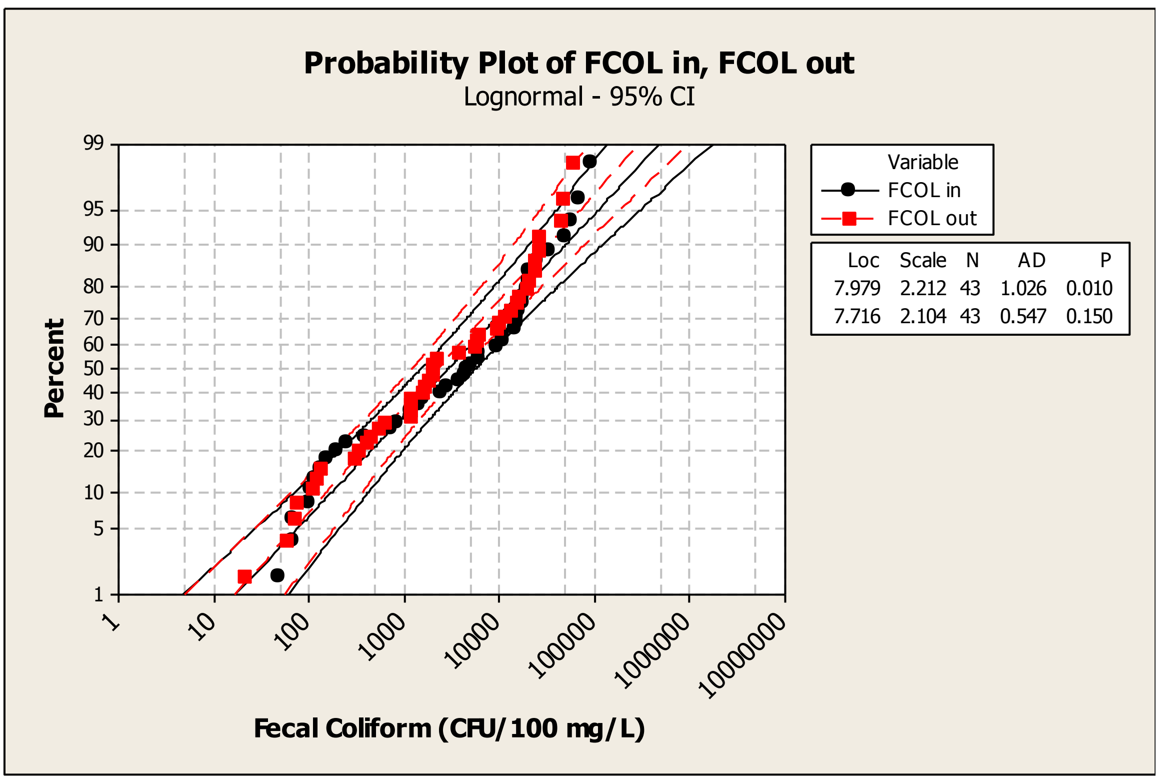

Figure 51 Probability Plots of Fecal Coliform Influent and Effluent

Boxplots of the influent and effluent fecal coliform concentrations are shown in Figure 52 and Figure 53, respectively. Both influent and effluent concentrations are significantly different among the sites (p = 0.016 and p = 0.008), with the difference essentially the result of the low concentrations observed at Jollyville.

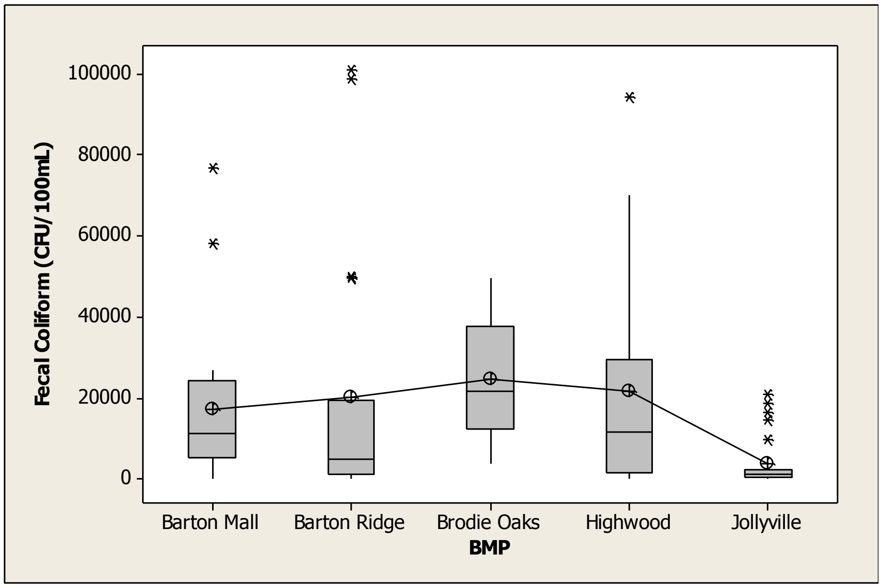

Figure 52 Boxplot of Fecal Coliform Influent Concentrations

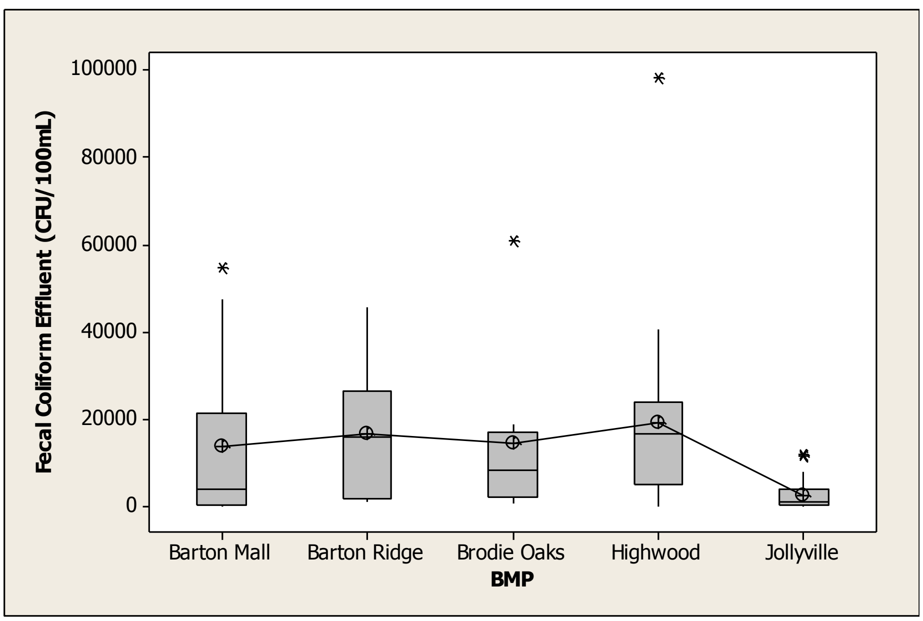

Figure 53 Boxplot of Fecal Coliform Discharge Concentrations

The performance of sand filters for bacteria removal has become a higher priority with the adoption in the Austin area of the TMDL for indicator bacteria in Gilleland Creek. When the paired data from all the sites is used to estimate bacteria removal, the removal is modest and the statistics indicate marginal certainty that removal has occurred. The performance for the individual sites is even more problematic, as shown in Table 17. The site with the least significant removal is Brodie Oaks; however, there are only four paired samples for analysis. None of the sites appear to have significant removal when all data are used (non-paired test), so it is critical to conduct the analysis with paired data only.

Table 17 Fecal Coliform Concentrations for Individual Sites based on Paired Data

Site	EMC in	EMC out	Efficiency Ratio	Wilcoxon SRT
Barton Mall	14,000	11,050	21	0.180
Barton Ridge	17650	18400	-4	0.375
Brodie Oaks	11,500	19,500	-70	1.000
Highwood	25500	11,700	54	0.754
Jollyville	3750	2100	44	0.607
All Sites	13,300	9700	27	0.007

A plot of influent versus effluent fecal coliform concentrations is presented in Figure 54. There is a substantial amount of scatter in the data, do it is difficult to draw any firm conclusions about the results. Influent and effluent concentrations are significantly related at both Jollyville and Highwood and these graphs are presented in Figure 55and Figure 56, respectively.

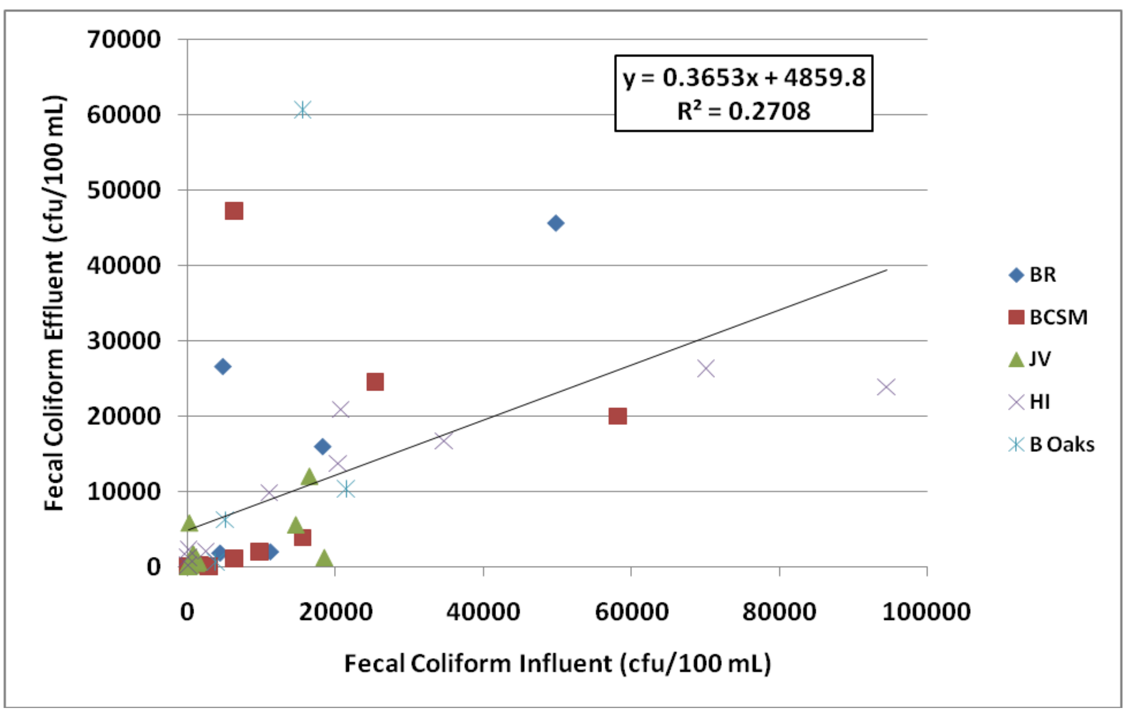

Figure 54 Relationship between FC Influent and Effluent Concentrations all Sites

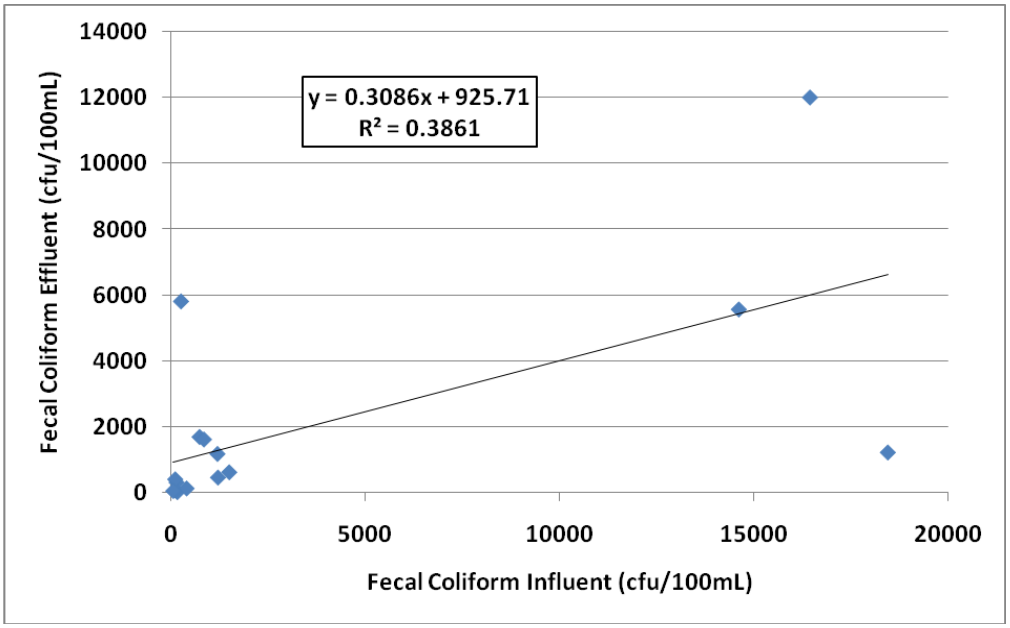

Figure 55 Relationship between FC Influent and Effluent Concentrations Jollyville

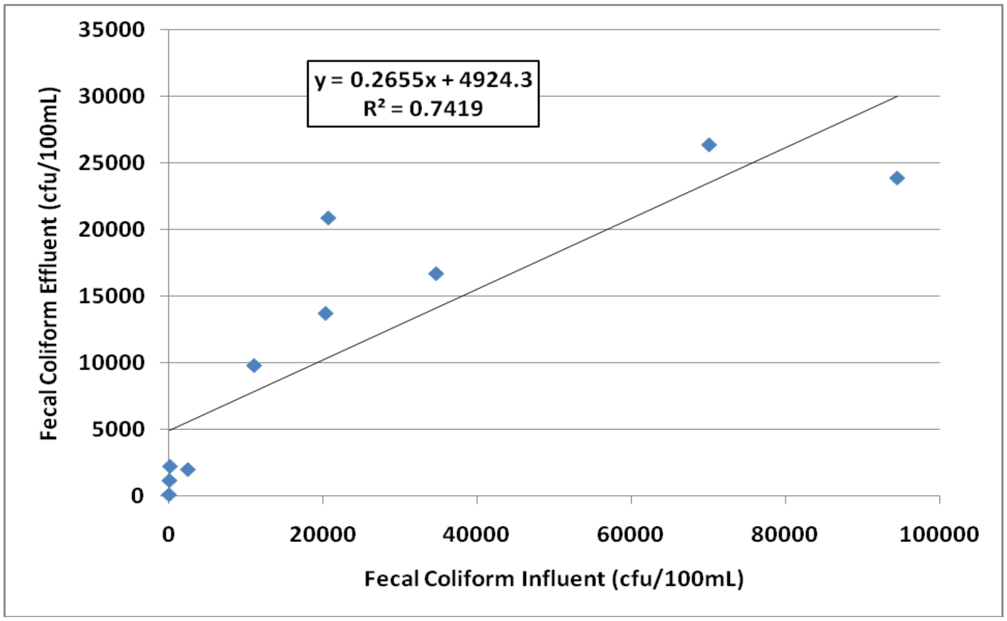

Figure 56 Relationship between FC Influent and Effluent Concentrations Highwood

A plot of time series of fecal coliform discharge concentrations at Jollyville are presented in Figure 57. There are only two events which exhibit a strong first flush effect, which suggests that re-growth or re-suspension of previously collected bacteria did not occur. The natural conclusion is that the bacteria are preferentially attached to the smallest size fraction, which is conveyed through the media with only modest removal.

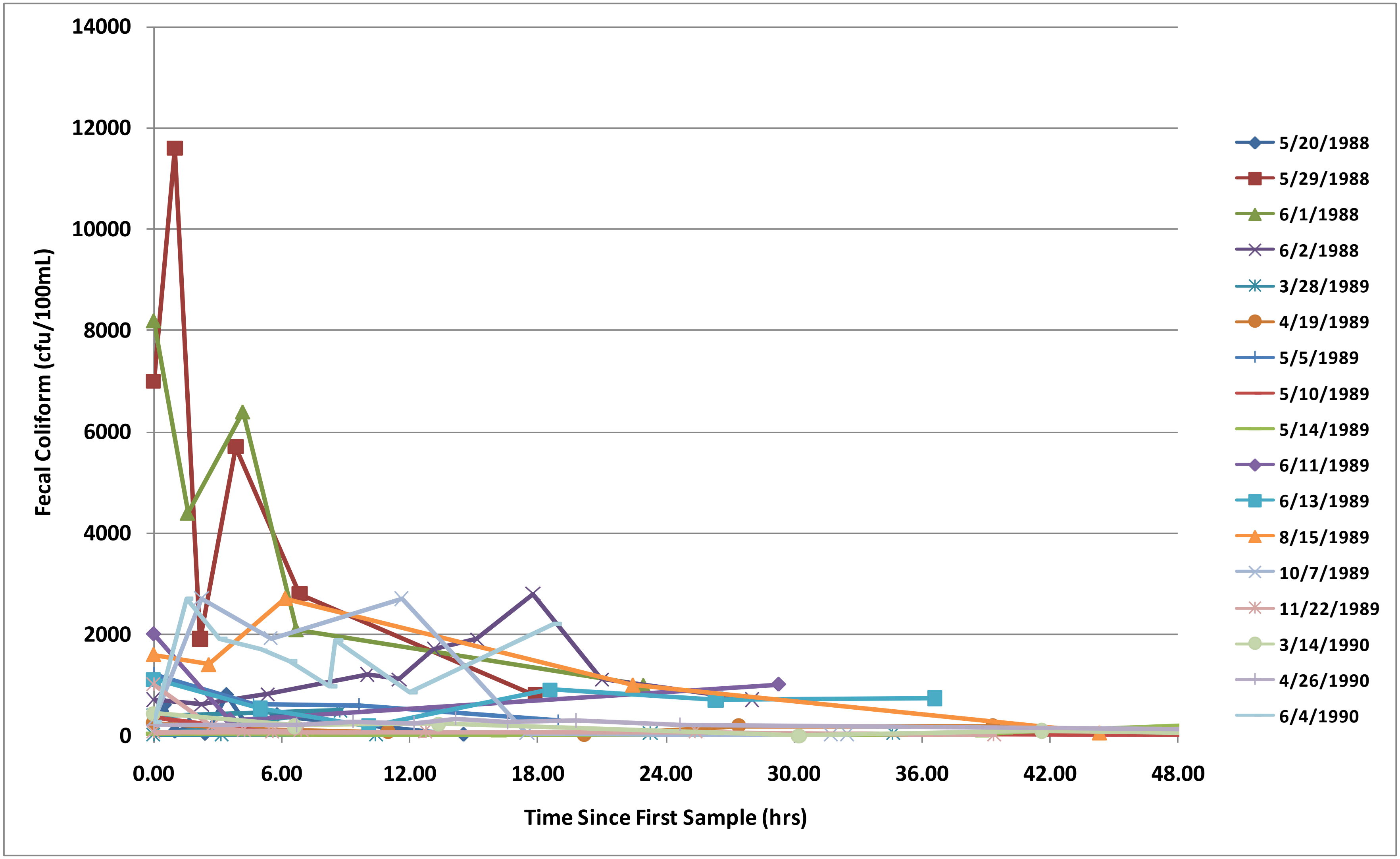

Figure 57 Temporal Trends for Fecal Coliform for Jollyville

Finally, Figure 58 presents a graph relating fecal coliform discharge concentration to hydraulic residence time at Jollyville. The relationship is significant ($p = 0.052$) and influent concentration does not seem to affect the discharge concentration. An attempt was made to develop this same relationship for several other sites without success. At Barton Creek Square Mall, the HRT for all the events fell in a narrow range from about 7 to 9 hours, with no obvious relationship apparent. The residence times at Barton Ridge are probably more related to mass balance issues than actual residence times. At that site effluent volumes ranges from 14% to 344% of influent volumes. In addition, as will be described later, fecal strep concentrations at Jollyville were not related to HRT at all.

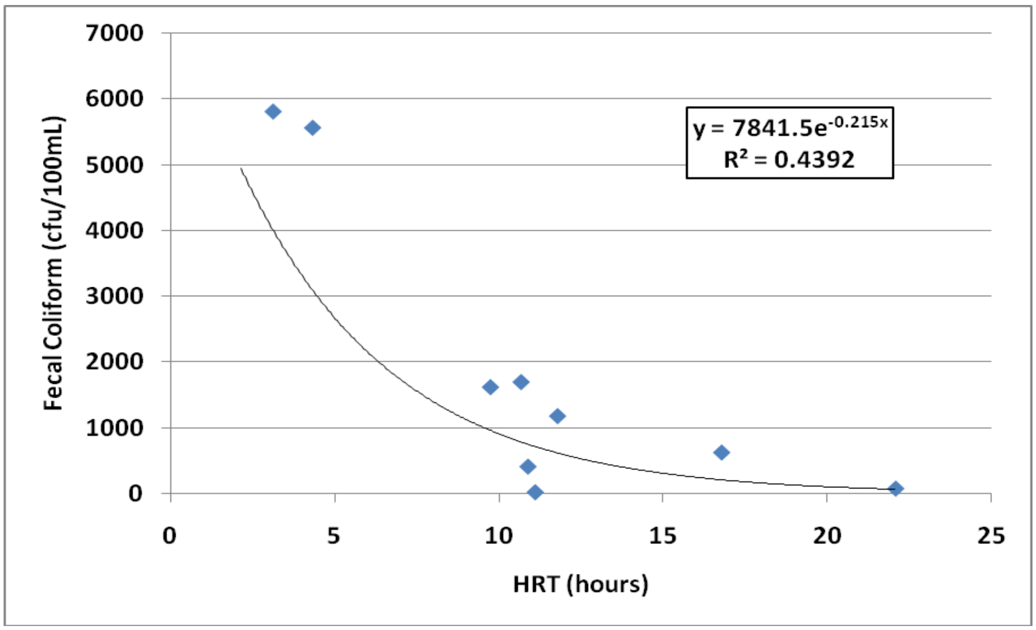

Figure 58 Relationship between Fecal Coliform Effluent Concentration and HRT at Jollyville

Fecal Coliform Conclusions:

1. Fecal coliform removal in the sand filters is modest and marginally significant statistically.

2. Discharge concentrations at Jollyville decreased with increasing residence times, although this could not be confirmed using data at the other sites.

3. There was only a subdued first flush for most events, which suggests that bacteria regrowth in the media and underdrain was not an important phenomenon.

9 Fecal Streptococcus Performance

Fecal Streptococcus is another bacteria indicator organism that has been used historically to assess the potential human health risks associated with stormwater.

As shown in Table 18, most of the fecal strep data are lognormally distributed. Figure 59 presents the cumulative probability plot of fecal strep influent and effluent concentrations using paired data from all the sites. The distributions are clearly more distinctly different than the fecal coliform data, which confirms the higher confidence that removal of fecal strep actually occurs than that observed for fecal coliform. Both the influent and effluent distributions are indistinguishable from the lognormal distribution.

Table 18 Statistical Distribution of Fecal Strep Data for Each Site

	Barton Mall	Barton Ridge	Brodie Oaks	Highwood	Jollyville	All sites
Influent	?	Normal/lognormal	Normal/ Lognormal	Lognormal	Lognormal	Lognormal
Effluent	Lognormal	Normal/lognormal	Lognormal	Normal/lognormal	Lognormal	Lognormal

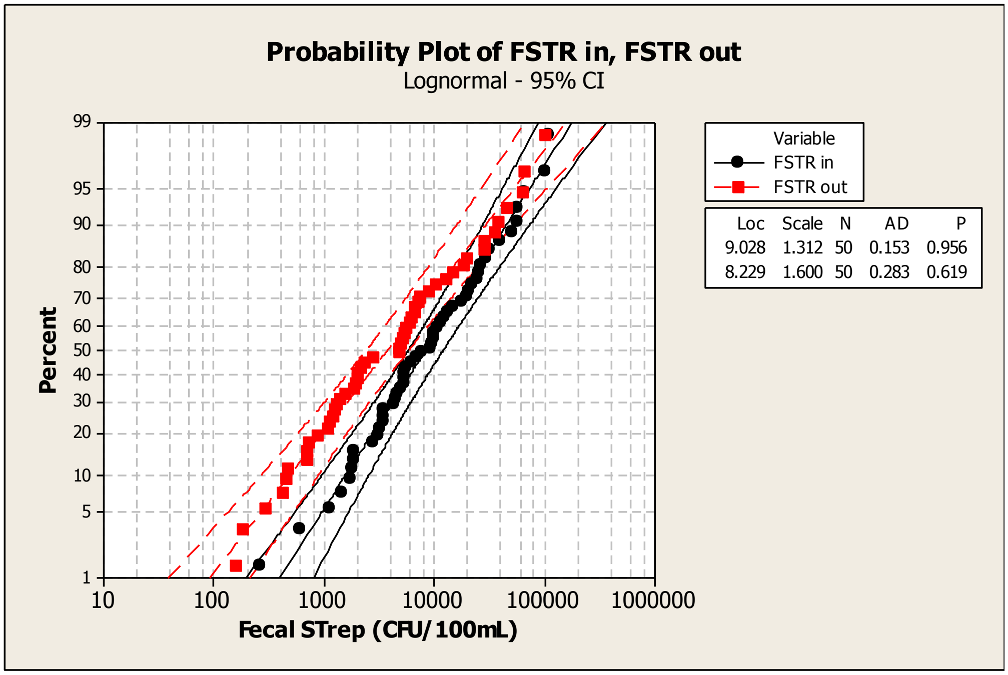

Figure 59 Probability Plots of Fecal Strep Influent and Effluent

Boxplots of influent and effluent concentrations are presented in Figure 60 and Figure 61, respectively. Influent concentrations at the various sites are not significantly different ($p = 0.144$); however, discharge concentrations are ($p = 0.029$). As can be seen in the two figures this difference is due primarily to a narrowing of the observed ranges in the effluent, since the relative relationships between the many sites remain the same (i.e., the high influent sites are the high effluent concentration sites).

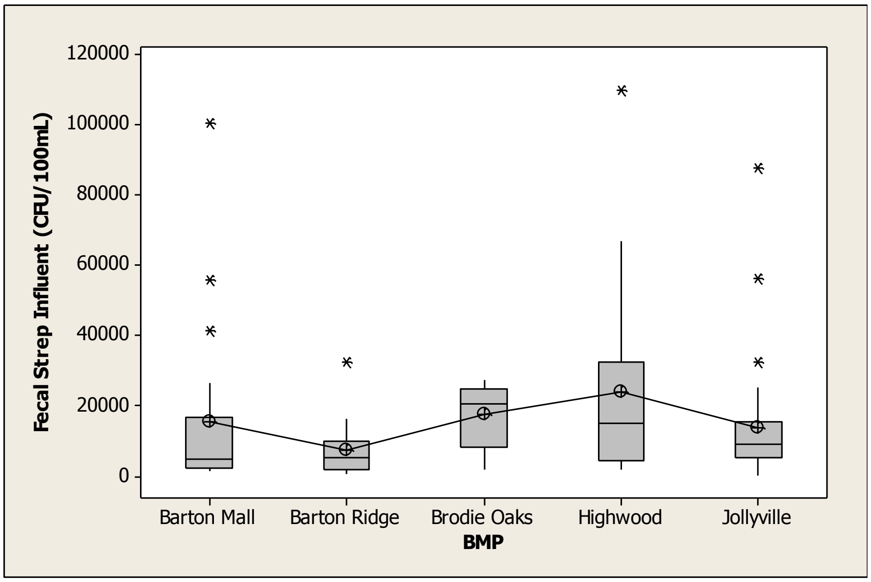

Figure 60 Boxplot of Fecal Strep Influent Concentrations

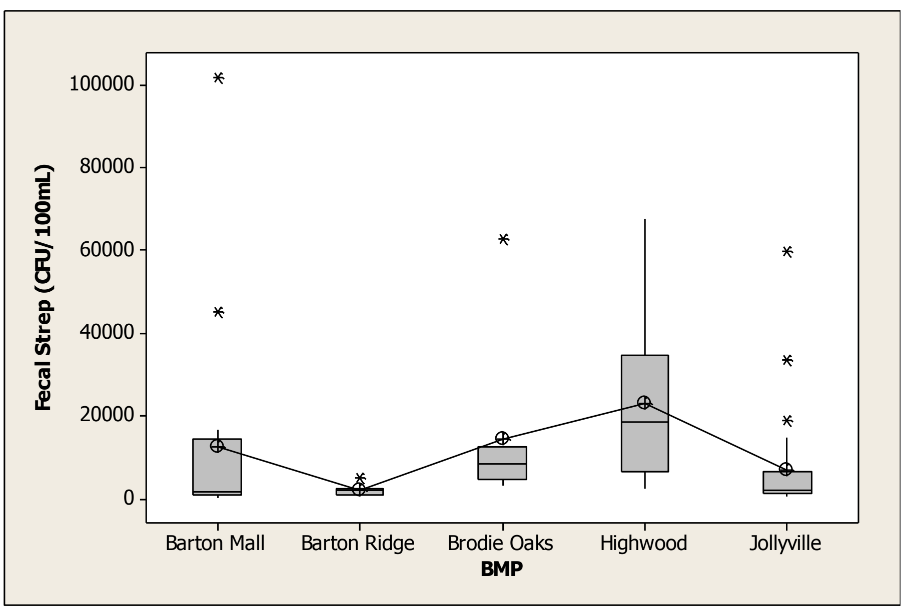

Figure 61 Boxplot of Fecal Strep Effluent Concentrations

On average, the concentrations of fecal strep are modestly reduced; however, the variability is much less than that observed for fecal coliform, which results in a more statistically significant relationship. The performance for the individual sites is presented below in Table 19.

Table 19 Fecal Strep Concentrations for Individual Sites based on Paired Data

Site	EMC in	EMC out	Efficiency Ratio	Wilcoxon SRT
Barton Mall	18,900	15,700	17	0.022
Barton Ridge	4,650	2,150	54	0.375
Brodie Oaks	21,900	19,500	11	0.375
Highwood	30,800	21,900	29	0.774
Jollyville	11,000	3,550	68	<0.000
All Sites	17,780	11,825	33	<0.000

This suggests that effluent concentrations should be correlated with influent concentrations. Figure 62 presents this relationship for all the sites. As can be seen the two variables are highly correlated (r^2 approximately 0.70). Given the other vagaries in bacteria analysis, the implication that 70% of the variability in effluent concentrations is directly correlated ($p = 0.001$) with influent concentrations is rather surprising. The correlation is also significant when all the sites are analyzed individually; however, the result at Brodie Oaks is unlikely to be real since the equation predicts that discharge quality improves with decreasing influent quality.

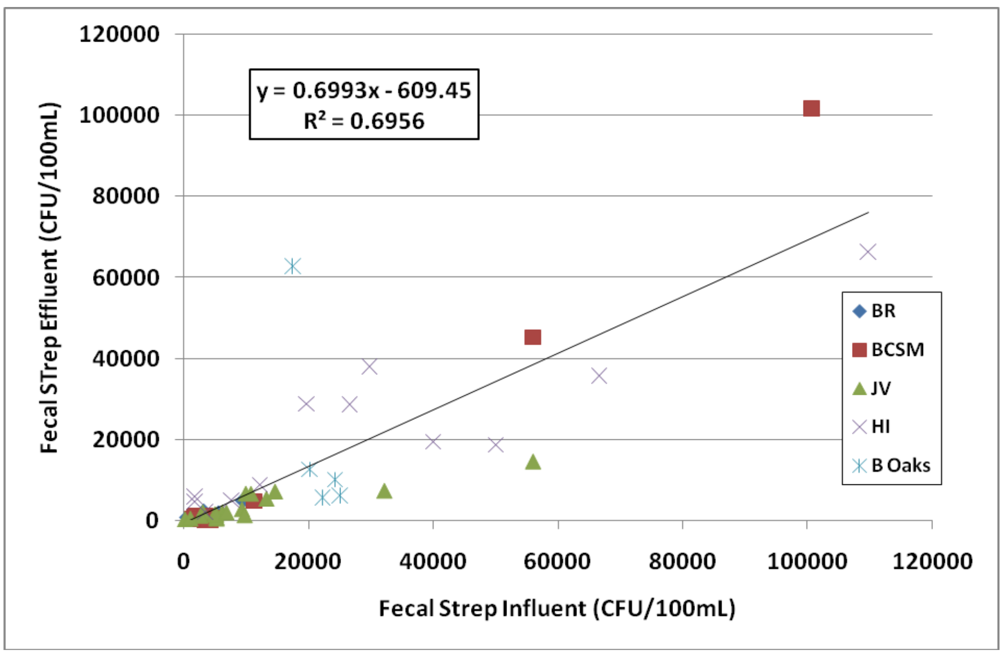

Figure 62 Relationship between Fecal Strep Concentrations (all sites)

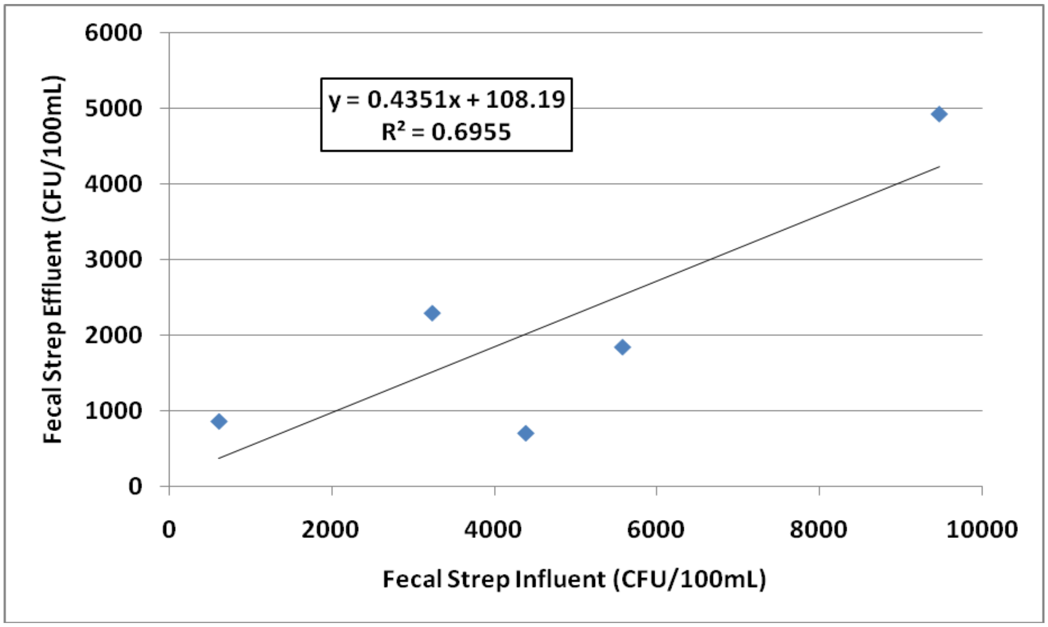

Figure 63 Relationship between Fecal Strep Concentrations for Barton Ridge

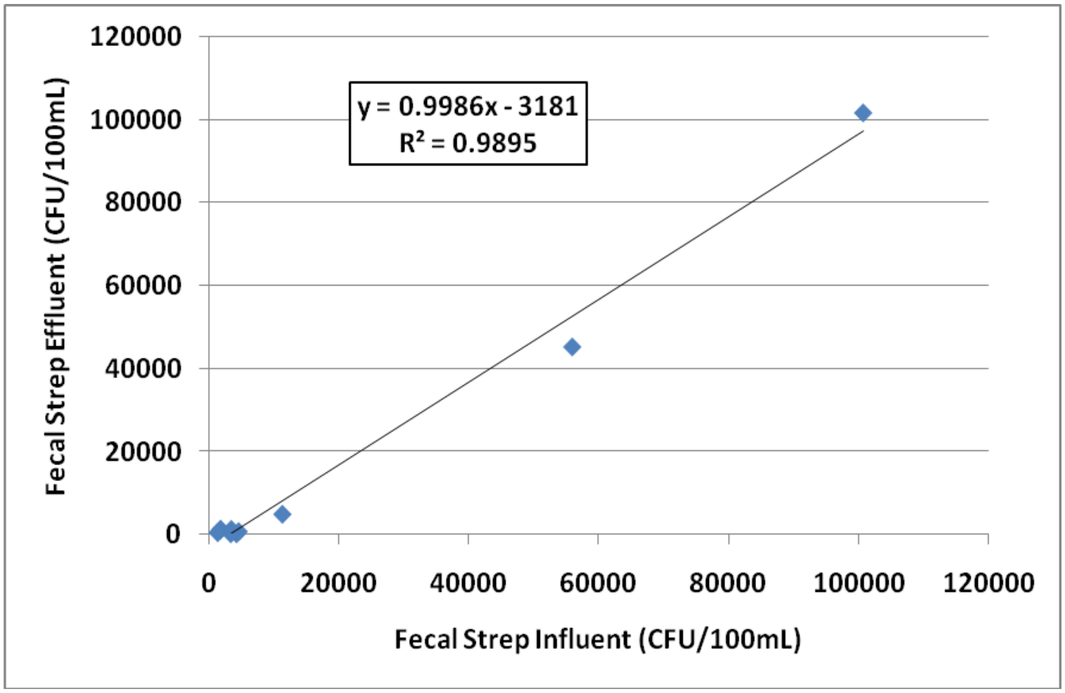

Figure 64 Relationship between Fecal Strep Concentrations Barton Mall

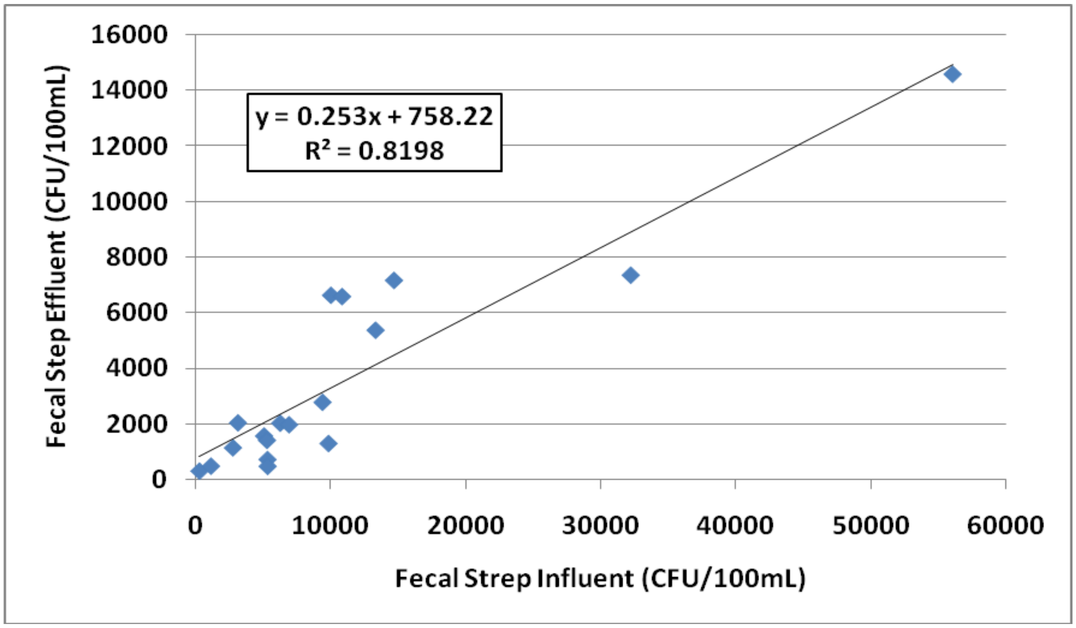

Figure 65 Relationship between Fecal Strep Concentrations Jollyville

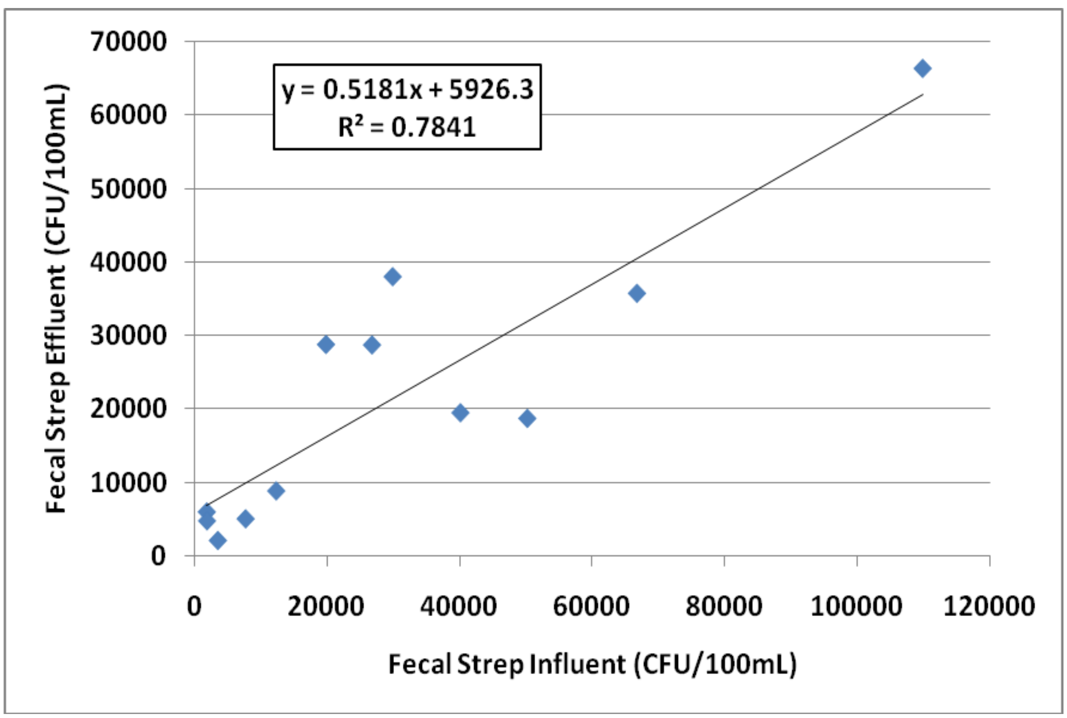

Figure 66 Relationship between Fecal Strep Concentrations Highwood

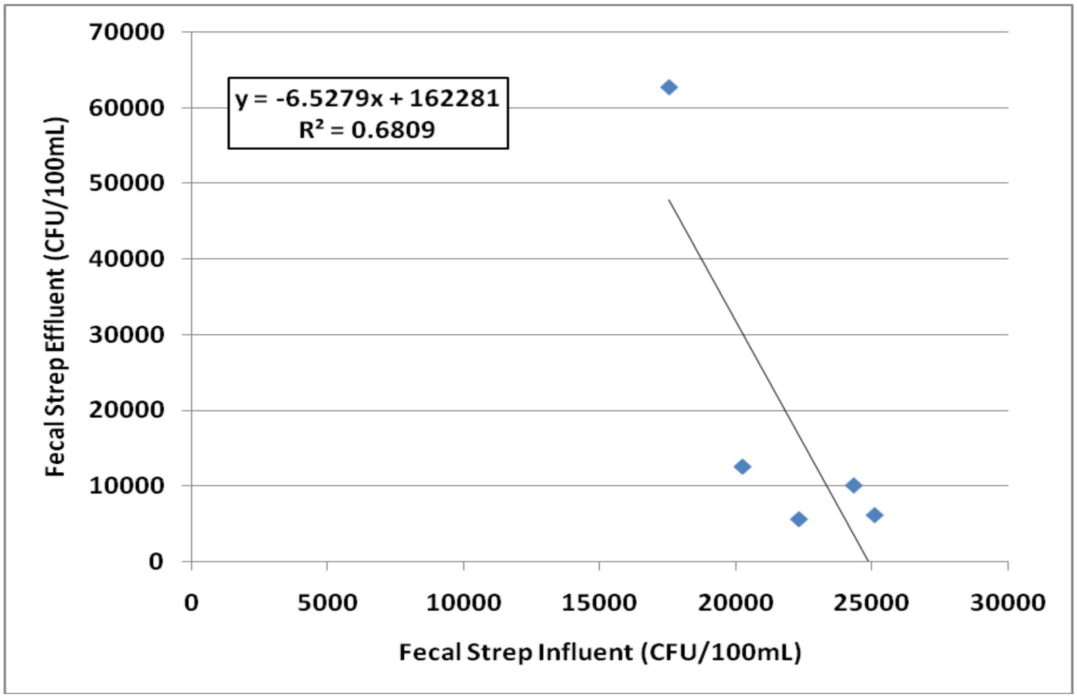

Figure 67 Relationship between Fecal Strep Concentrations Brodie Oaks

A multiple regression was also performed to determine if HRT as well as influent concentration affected discharge concentrations; however, HRT was not a significant predictor ($p = 0.342$). This suggests that die-off and predation on the bacteria in the filter is not very substantial either because the bacteria within the media are protected from sunlight or because the rather sterile media does not support a very large community of bacteria predators.

The temporal pattern of fecal strep discharge concentrations at Jollyville are presented in Figure 68. There are a couple of events with very high and erratic concentrations reported, but most of the events have only a modest first flush type response.

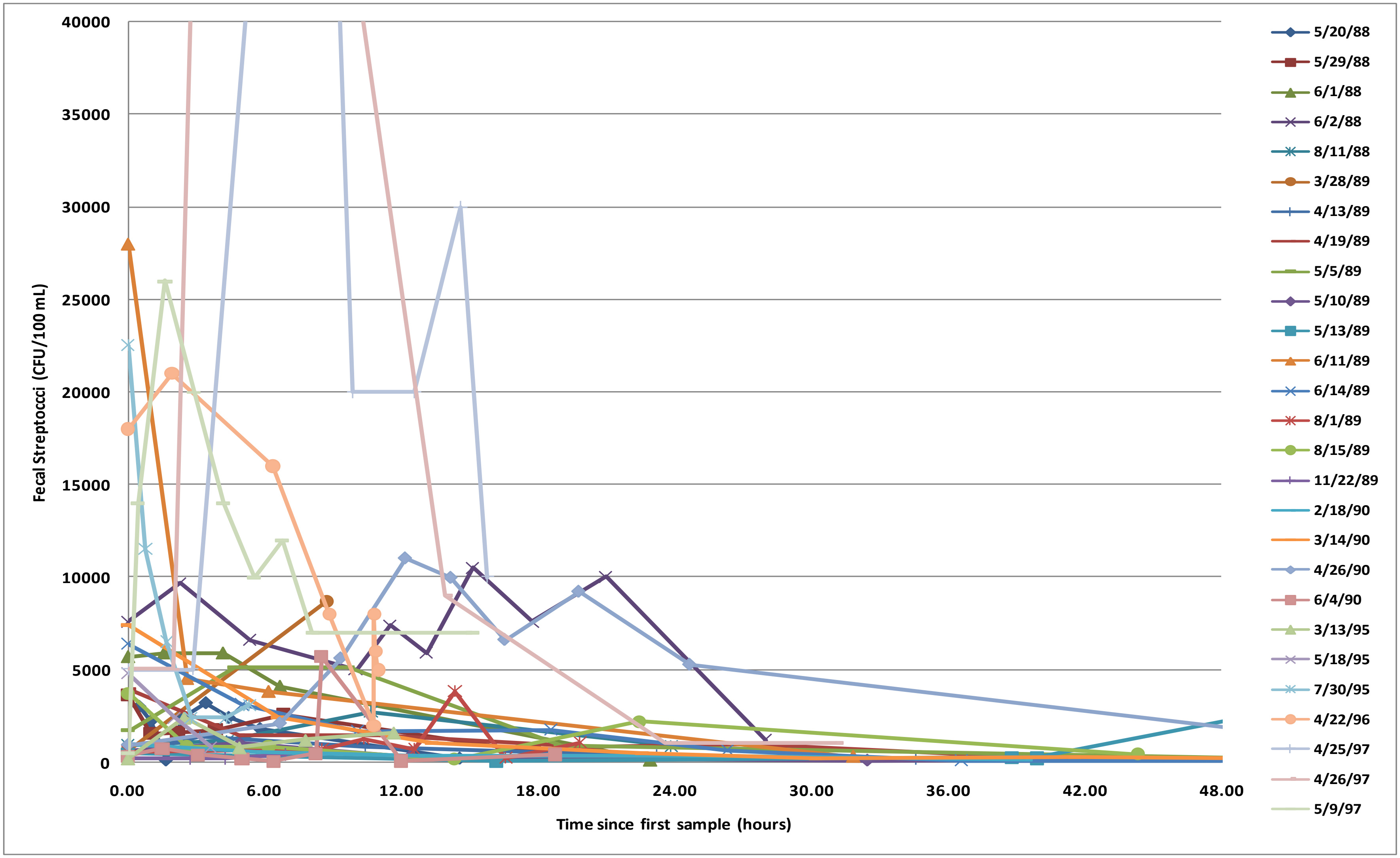

Figure 68 Temporal Pattern of Fecal Strep Discharge Concentrations at Jollyville

Fecal Strep Conclusions:

1. Statistically significant reduction in concentrations occur; however, the reduction is not large (roughly 30%).
2. The discharge concentrations at the various sites are significantly different, but this is primarily the result of different influent concentrations.
3. HRT is not a significant predictor of discharge quality for fecal strep.

10 Biochemical Oxygen Demand (BOD) Performance

The distribution of measured BOD concentrations tends to be highly lognormal at the individual sites, as shown in Table 20. Figure 69 presents the cumulative probability plots of influent and effluent concentrations for the pooled data. The plots are distinctly different which supports the earlier finding that significant BOD reduction occurs in sand filters. Note that the effluent concentrations are not lognormally distributed.

Table 20 Statistical Distribution of BOD Data for Each Site

	Barton Mall	Barton Ridge	Brodie Oaks	Highwood	Jollyville	All sites
Influent	Lognormal	Lognormal	?	Lognormal	Lognormal	Lognormal
Effluent	Lognormal	?	Lognormal	Lognormal	?	?

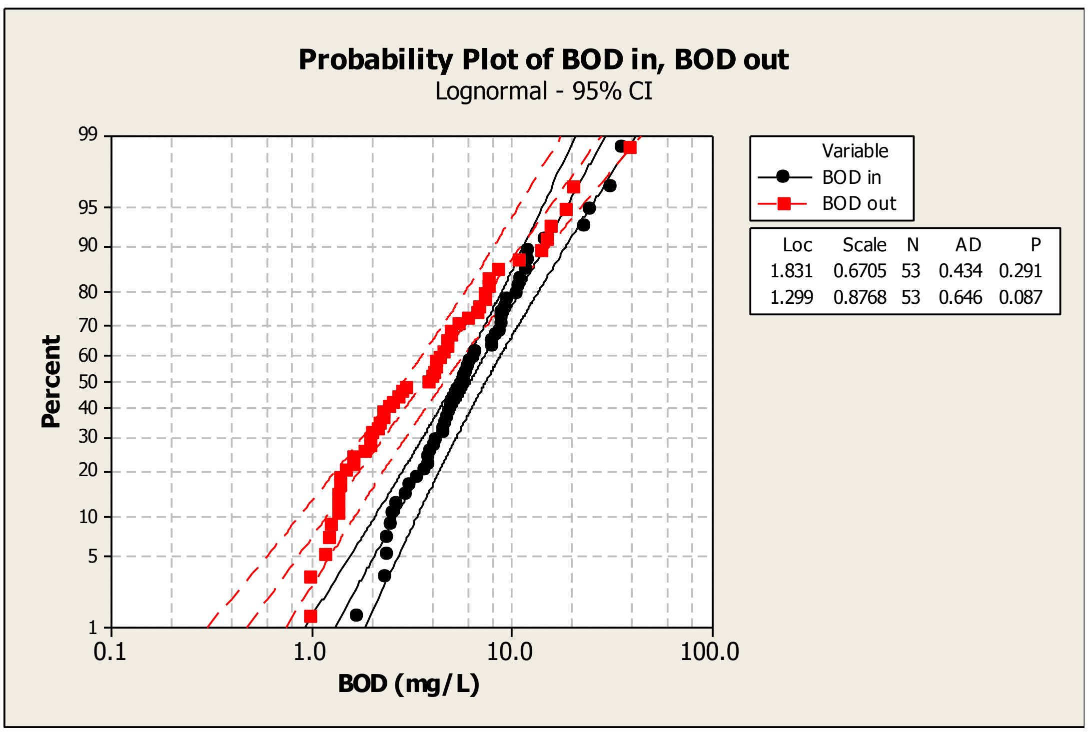

Figure 69 Probability Plots of BOD Influent and Effluent

Boxplots of BOD influent and effluent concentrations are presented in Figure 70 and Figure 71, respectively. BOD Influent concentrations not significantly different (p = 0.345), but effluent concentrations are different (p = 0.002), mostly due to low concentrations observed at Barton

Ridge and Jollyville. It's not apparent what causes the difference in performance for these two systems, since their designs have almost nothing in common. One potential explanation is that the BOD in the influent is more associated with the solid phase and, consequently, is more easily removed.

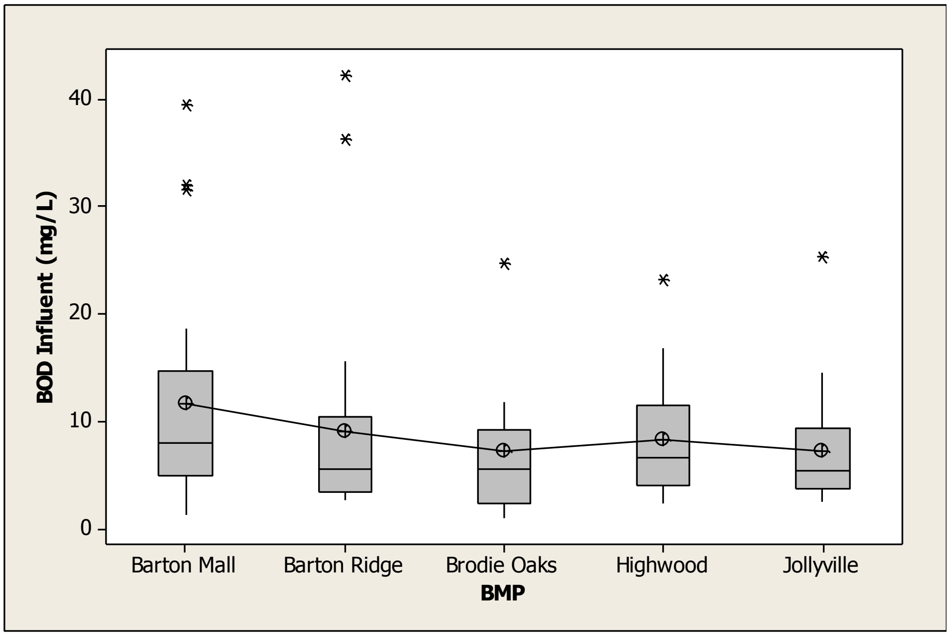

Figure 70 Boxplot of BOD Influent Concentrations

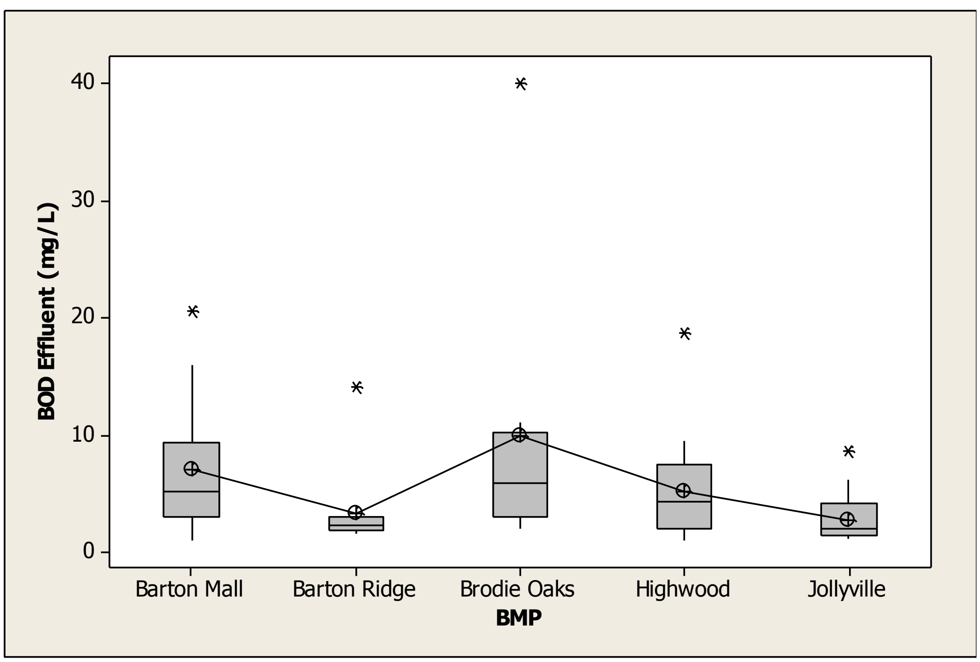

Figure 71 Boxplot of Effluent BOD Concentrations

Mean influent and effluent BOD concentrations for the five sites are presented in Table 21. Performance is quite variable among the sites, with the worst performance occurring at Brodie Oaks, although there are only 5 storms at that site with paired data.

Table 21 BOD Concentrations for Individual Sites based on Paired Data

Site	EMC in	EMC out	Efficiency Ratio	Wilcoxon SRT
Barton Mall	9.2	7.3	18	0.065
Barton Ridge	8.5	3.8	55	0.039
Brodie Oaks	10.1	12.8	-27	1.000
Highwood	8.5	6.3	26	0.344
Jollyville	6.0	2.7	55	<0.000
All Sites	8.0	5.6	30	<0.000

Figure 72 presents a regression analysis of influent and effluent concentrations for all the sites pooled together. The regressions for all the sites individually are also statistically significant and those figures are presented in Figure 73 through Figure 77. It should be noted that although the regression is significant, the analysis of paired data indicate that substantial removal of BOD does not occur at either Brodie Oaks or Highwood.

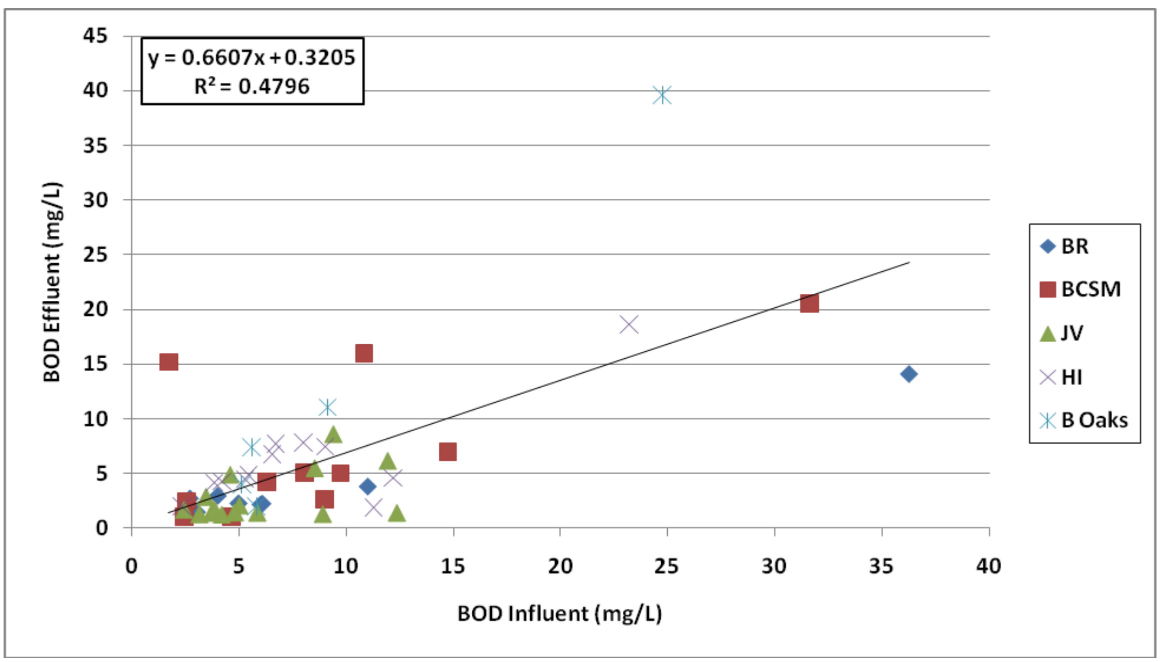

Figure 72 Relationship Between Influent and Effluent BOD Concentrations

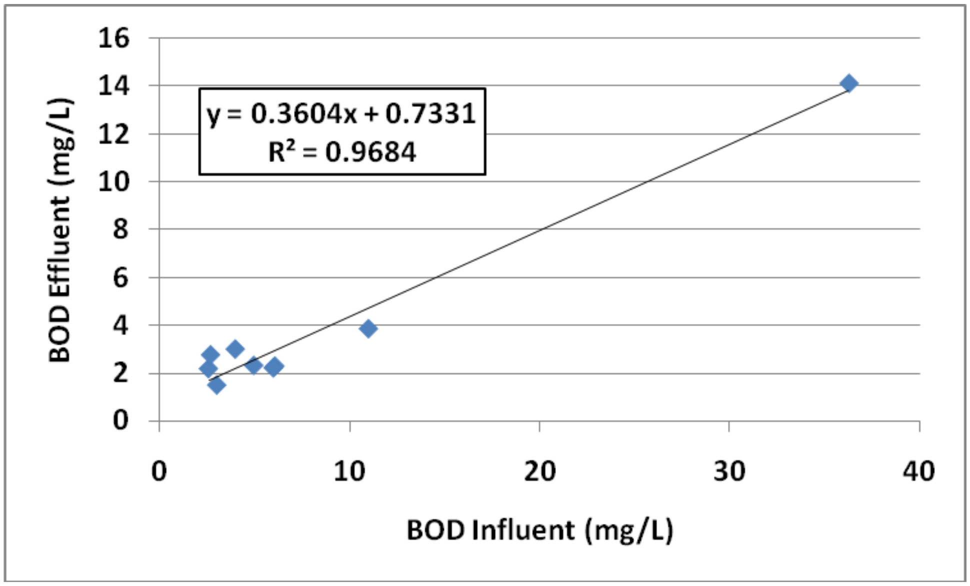

Figure 73 Relationship Between Influent and Effluent BOD Concentrations Barton Ridge

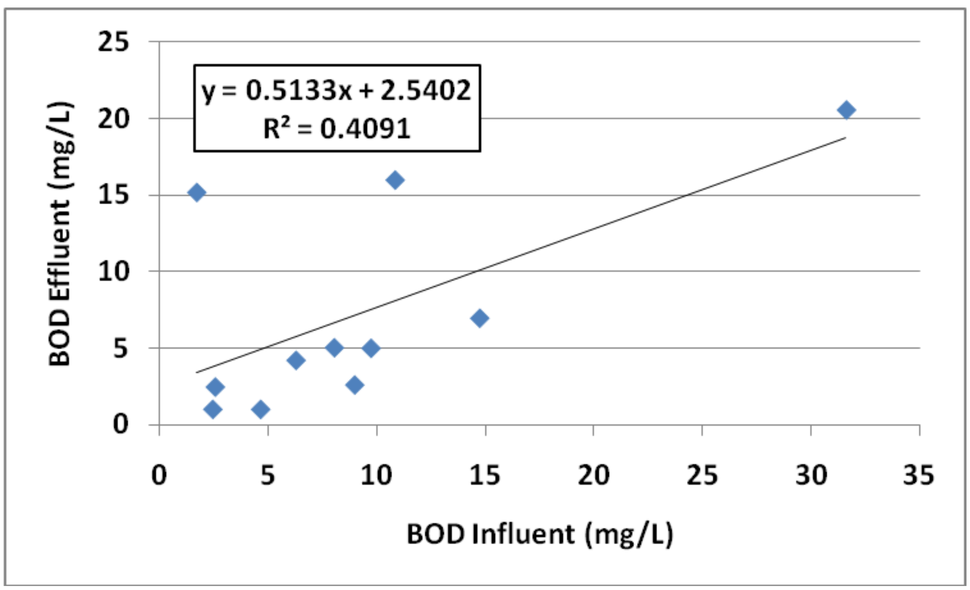

Figure 74 Relationship Between Influent and Effluent BOD Concentrations Barton Mall

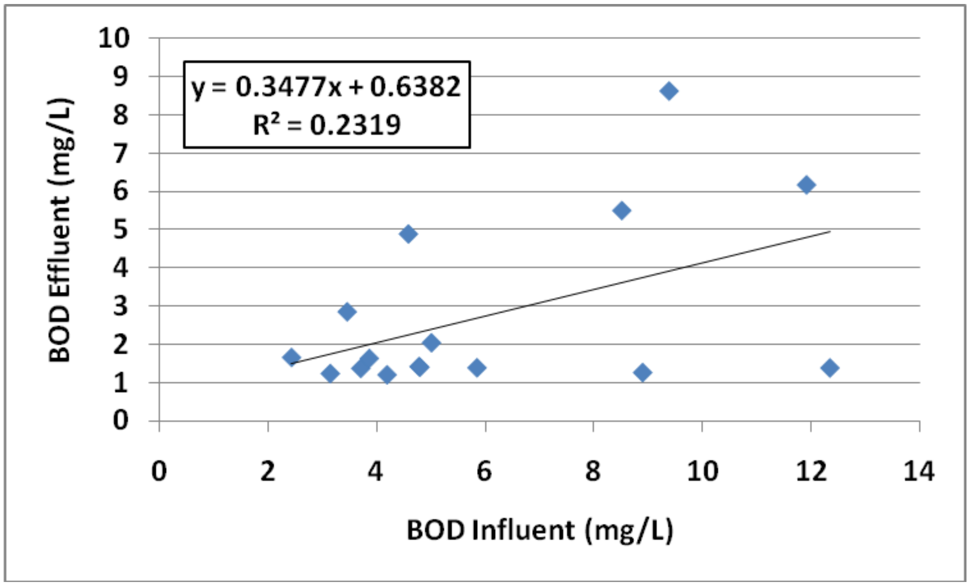

Figure 75 Relationship Between Influent and Effluent BOD Concentrations Jollyville

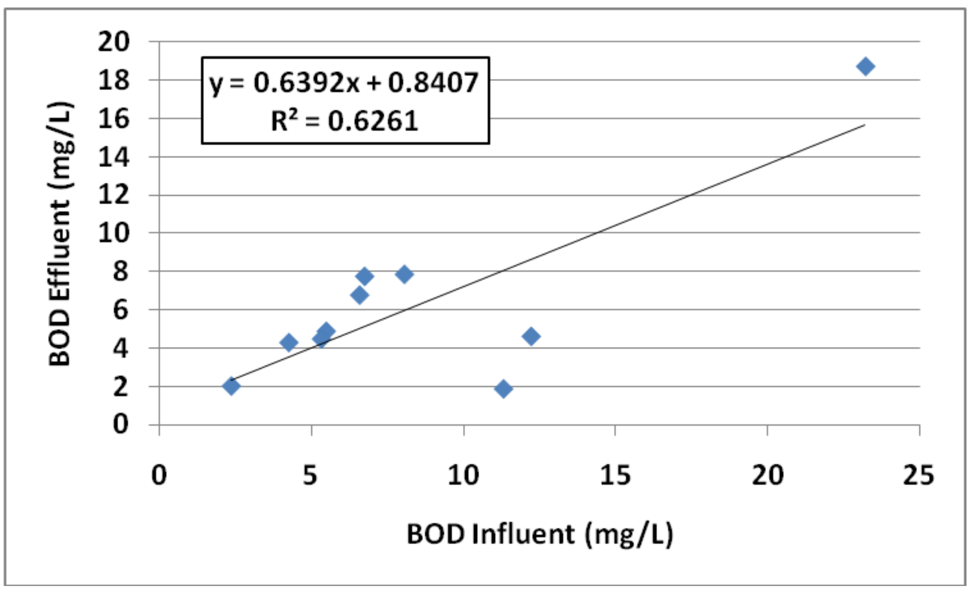

Figure 76 Relationship Between Influent and Effluent BOD Concentrations Highwood

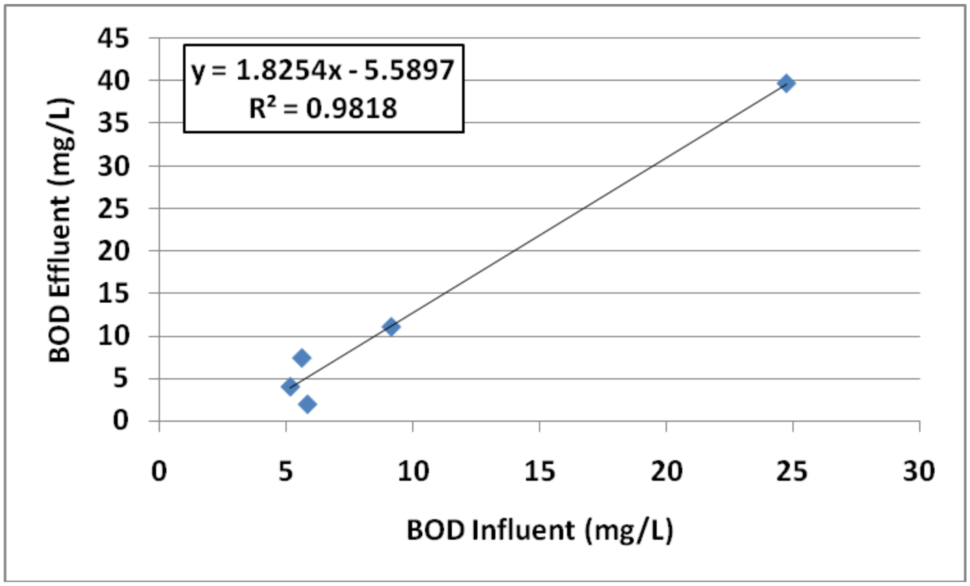

Figure 77 Relationship Between Influent and Effluent BOD Concentrations Brodie Oaks

The temporal pattern of BOD discharge from a sand filter is illustrated in Figure 78, which shows a fairly consistent first flush pattern, much like that observed for TSS. Figure 72 presents a graph of influent versus effluent concentrations. The relationship between the two is fairly strong ($r^2 = 0.48$), so this is a reasonably good way to estimate removal efficiency or discharge concentration.

Using the data at Jollyville, an estimate was also made of the relationship between HRT and BOD discharge concentration. The data are presented in Figure 79, which show a marked decrease in discharge concentration with increasing residence time. This suggests that some oxidation of organic material does occur during the storm event. A multiple regression was also performed which indicated that both HRT ($p = 0.024$) and influent concentration ($p = 0.064$) were significant predictors, with overall p value equal to 0.012. The following equation results:

$$BOD_e = 0.308 \times BOD_i - 0.227 \times HRT$$

A nonlinear formulation can also be developed, which relates the BOD discharge concentration to a power of the hydraulic residence time, which results in a p value of 0.006. In this formulation presented below, influent concentration is not a significant variable. This simple relationship did not hold for the data from Barton Creek Square Mall or Highwood, however.

$$BOD_e = 7.48 \times e^{-0.103HRT}$$

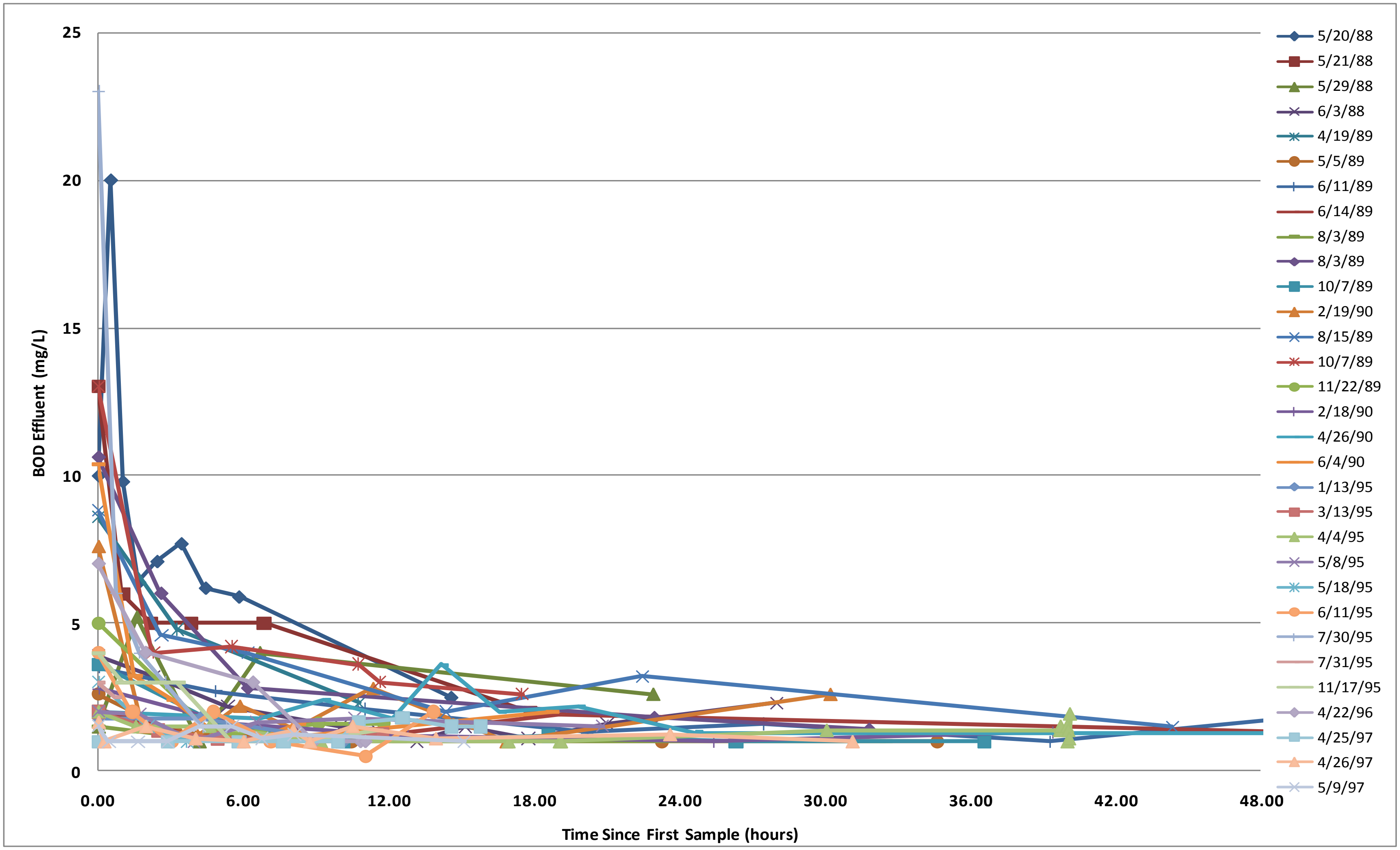

Figure 78 Temporal Pattern of BOD Discharge Concentrations at Jollyville

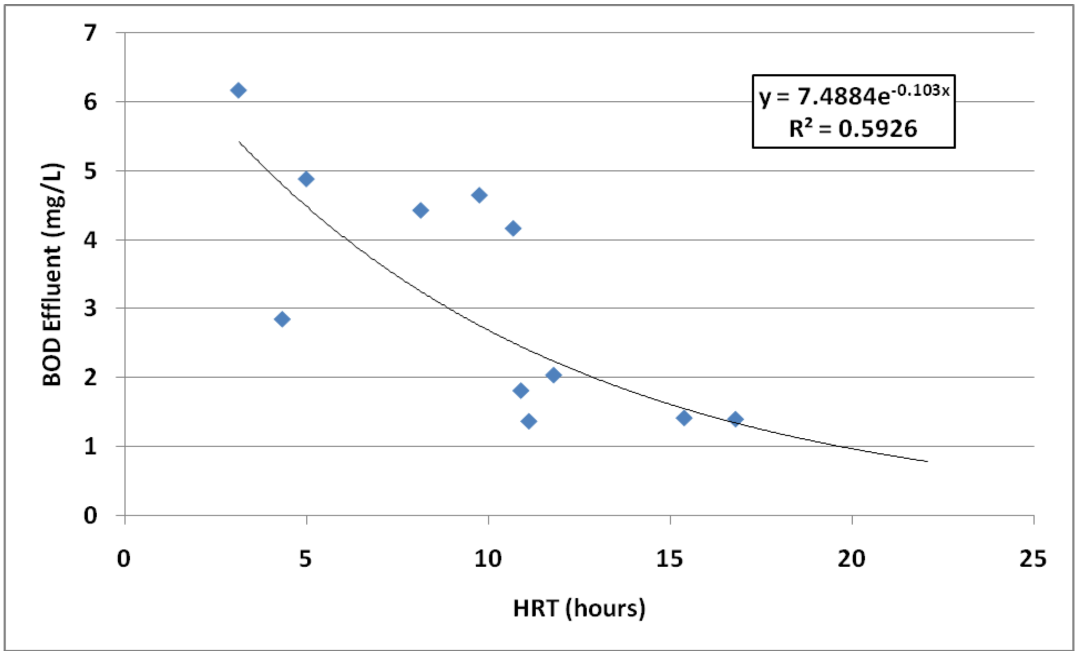

Figure 79 Relationship between BOD Effluent Concentration and HRT

BOD Conclusions

1. Removal of BOD in sand filters is statistically significant.

2. BOD discharge concentrations are significantly different, mostly due to low concentrations at Jollyville and Barton Ridge; however, it is not clear what is responsible for the higher removal unless it is related to influent concentrations at those two sites that are more particle associated.

3. BOD effluent concentrations at Jollyville were significantly related to HRT, but this was not observed at the other sites. In addition, it seems unlikely that substantial oxidation of the organic matter would occur in a matter of hours, since it often takes several days for substantial oxygen demand to be exerted in the laboratory.

11 Chemical Oxygen Demand (COD) Performance

As shown in Table 22, the data at most of the sites are lognormally distributed. Cumulative probability plots of influent and effluent COD concentrations for all the paired data from the pooled sites is presented in Figure 80. The distributions are very distinct, providing confirmation that the removal of COD is statistically significant.

Table 22 Statistical Distribution of COD Data for Each Site

	Barton Mall	Barton Ridge	Brodie Oaks	Highwood	Jollyville	All sites
Influent	Lognormal	Lognormal	Lognormal/normal	?	Lognormal/ normal	Lognormal
Effluent	Lognormal	Lognormal	Lognormal/normal	Lognormal/normal	Lognormal	Lognormal

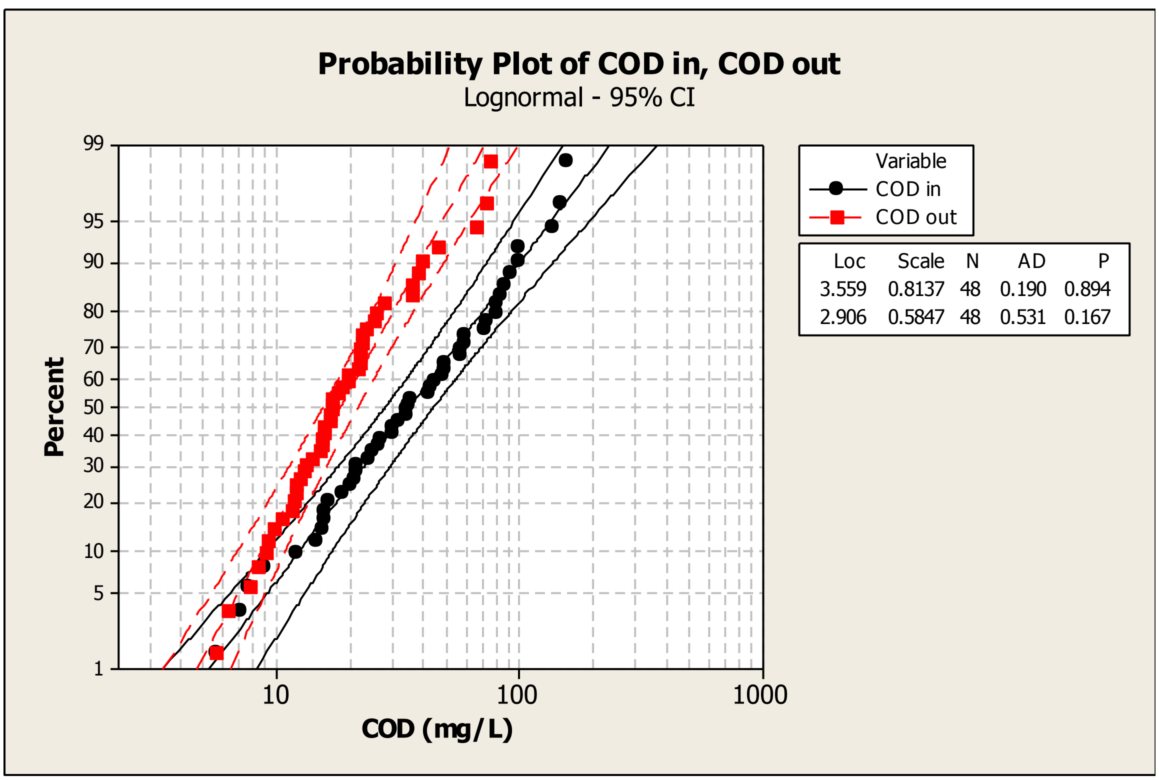

Figure 80 Probability Plot of COD Influent and Effluent Concentrations

Boxplots of COD influent and effluent concentrations are presented in Figure 81 and Figure 82, respectively. Influent and effluent concentrations are significantly different at the five sites (p < 0.000, and p = 0.056). To a large extent the differences in effluent concentration mirror the differences in influent concentration at all the sites except Barton Creek Square Mall, where the effluent concentrations are relatively high compared to the other sites.

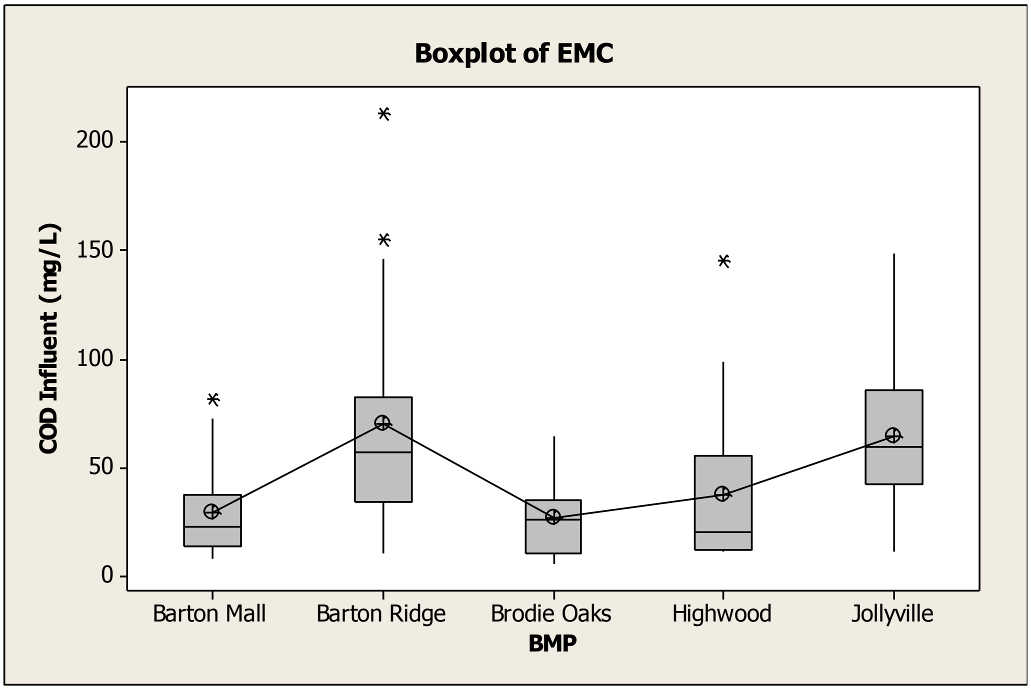

Figure 81 Boxplot of COD Influent Concentrations

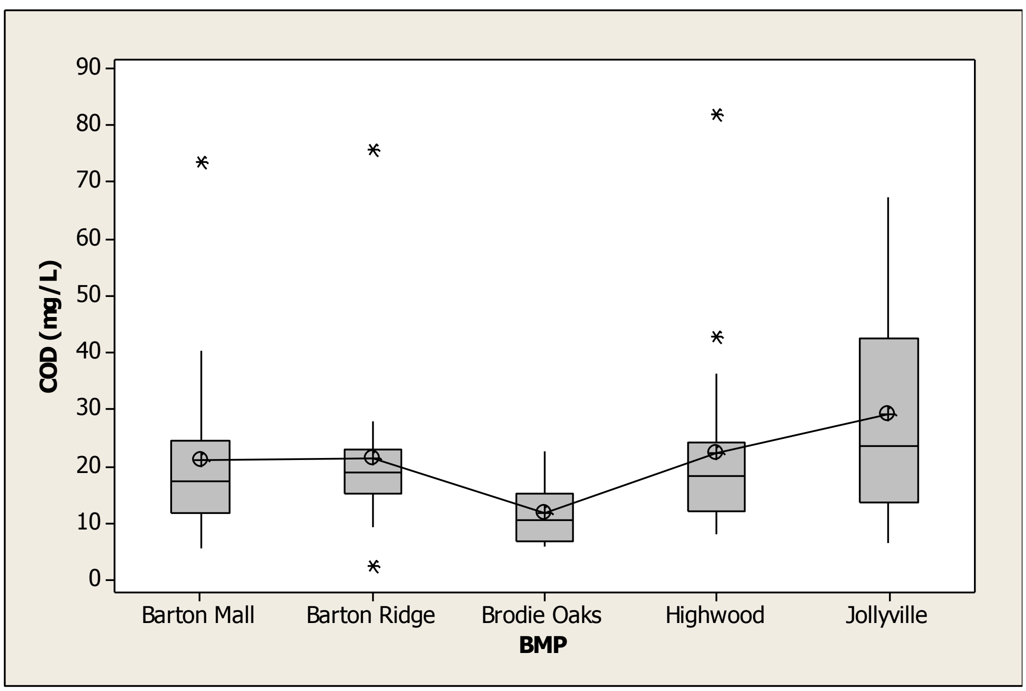

Figure 82 Boxplot of COD Effluent Concentrations

Average COD concentrations for the five sites are presented in Table 23. The effect of influent concentration on the efficiency ratio is again apparent with the cleanest watershed (Highwood) resulting in the lowest removal and worst t-test result, and the dirtiest watershed (Jollyville) having the best apparent performance and strongest statistical result.

Table 23 COD Concentrations for Individual Sites based on Paired Data

Site	EMC in	EMC out	Efficiency Ratio	Paired t-test
Barton Mall	59	26	57	0.227
Barton Ridge	59	25	58	0.004
Brodie Oaks	12	9	25	0.375
Highwood	29	18	38	0.065
Jollyville	78	25	68	<0.000
All Sites	47	22	53	<0.000

Figure 83 presents a linear regression of influent and effluent COD concentrations. There is a reasonable relationship between the two, although a number of values for Barton Creek Square Mall appear to be abnormally high. One factor that explains this is that those three events are represented by just three samples. Consequently, the initially high sample concentrations get used to represent a substantial percentage of the total storm event, driving up the calculated average concentration. Linear regressions for individual sites were also significant for Barton Ridge, Highwood, and Brodie Oaks. These regressions are presented in Figure 84 through Figure 86.

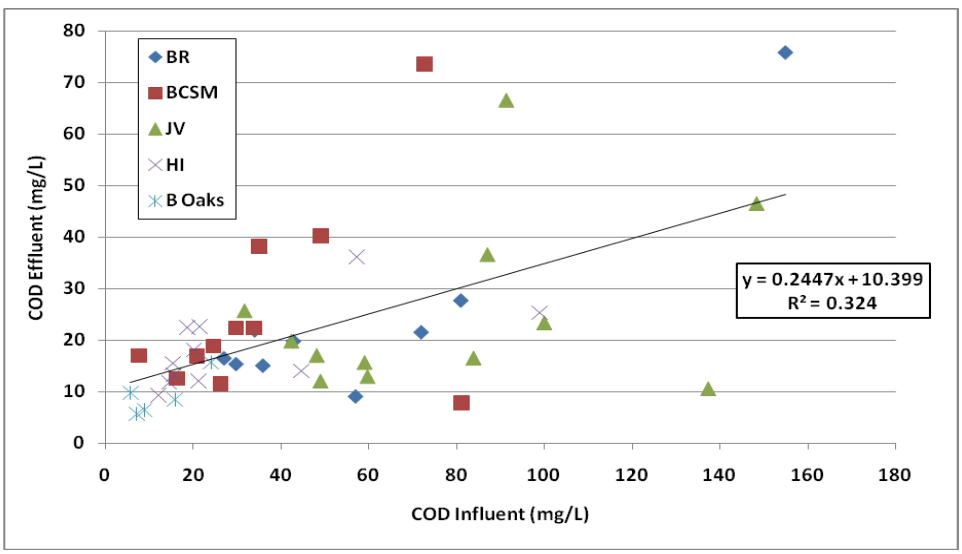

Figure 83 Relationship between COD Influent and Effluent Concentrations all Sites

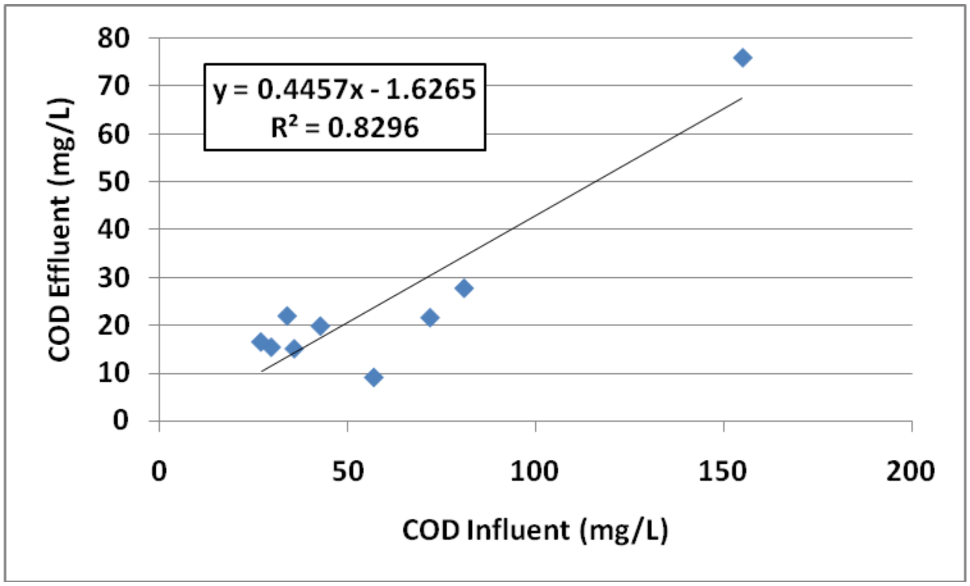

Figure 84 Relationship between COD Influent and Effluent Concentrations Barton Ridge

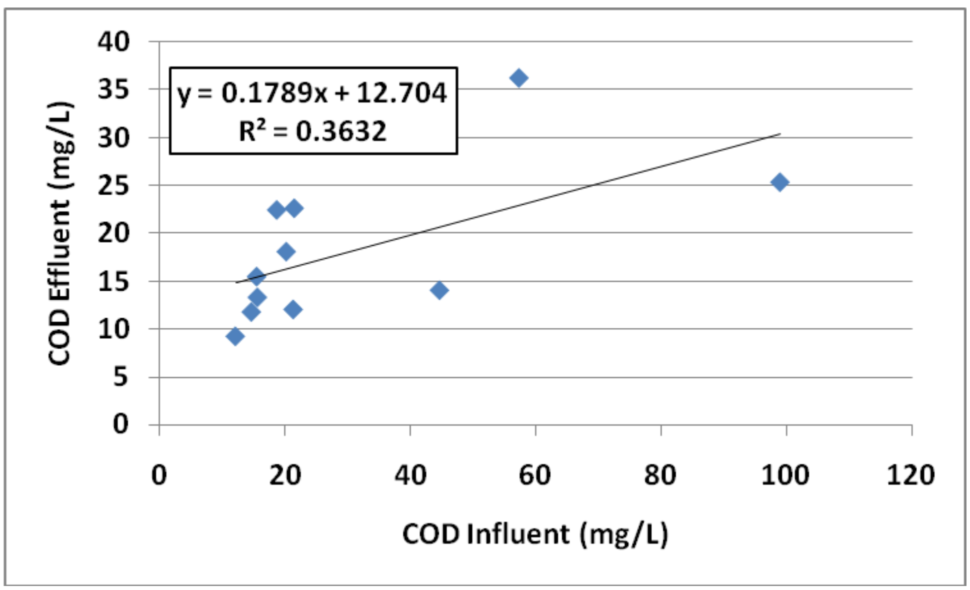

Figure 85 Relationship between COD Influent and Effluent Concentrations Highwood

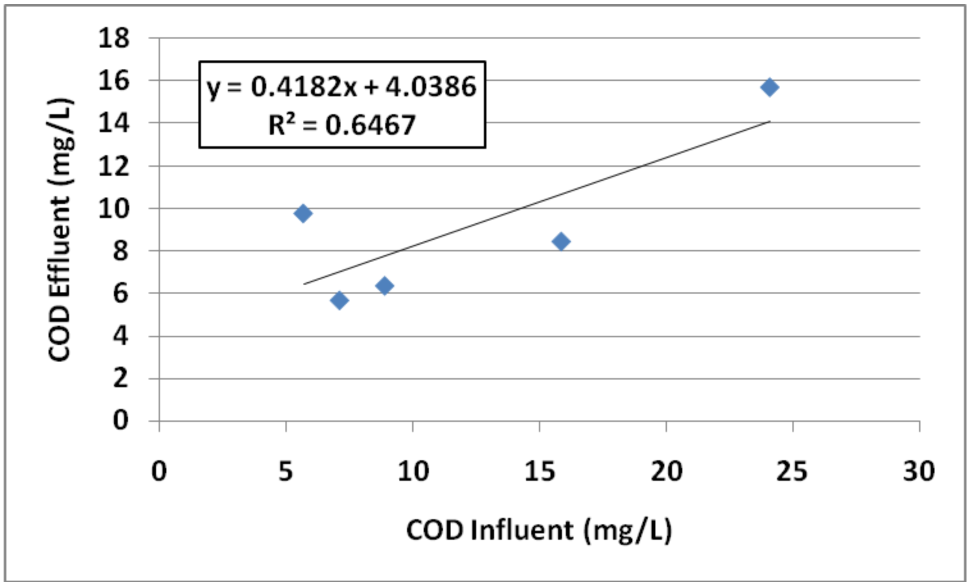

Figure 86 Relationship between COD Influent and Effluent Concentrations Brodie Oaks

The temporal pattern of discharge concentrations for Jollyville is presented in Figure 87. There is a substantial first flush effect, with discharge concentrations after about 6 hours exhibiting only a gradual decline through time.

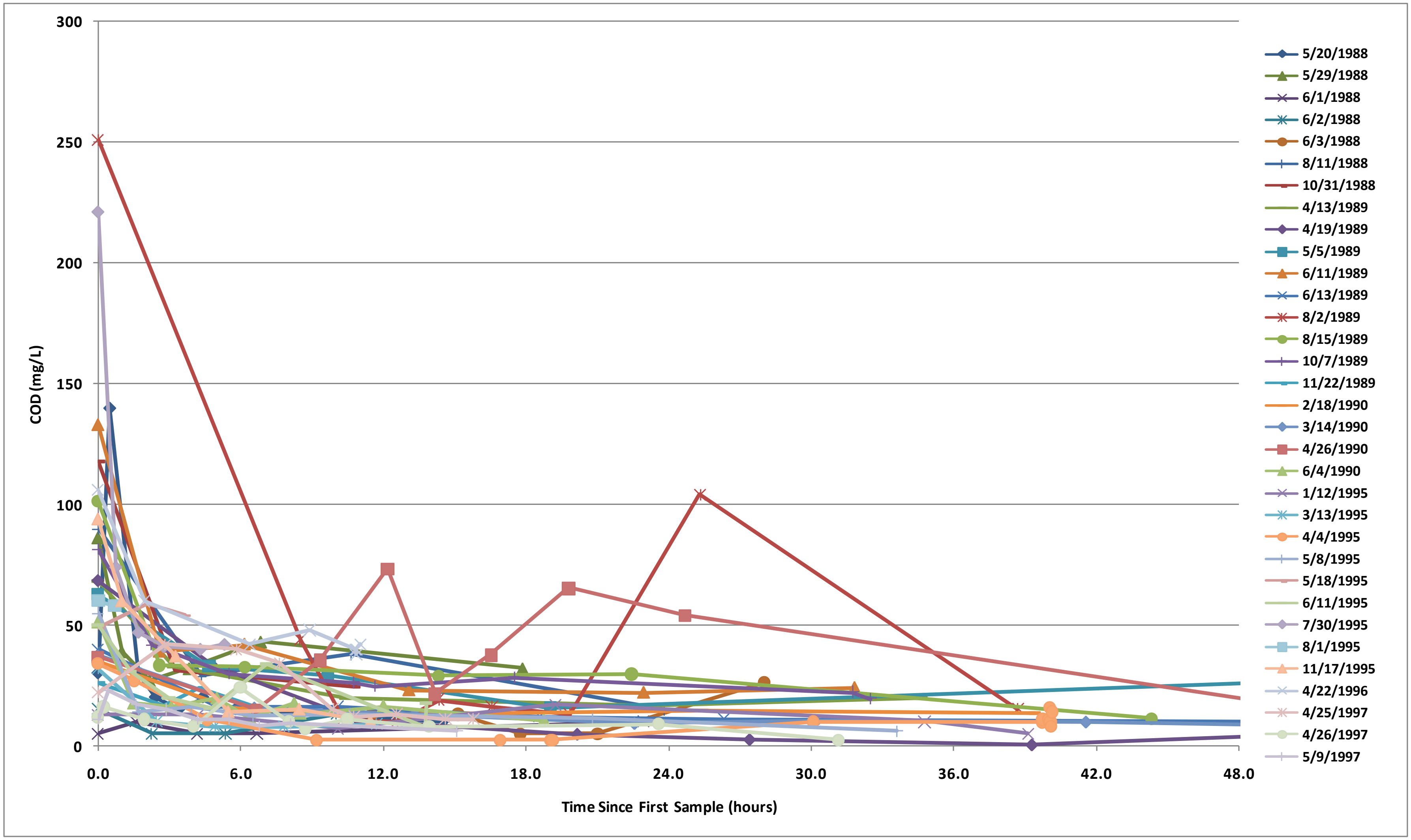

Figure 87 Temporal Pattern of COD Discharge Concentrations at Jollyville

Several different formulations were tried to determine the impact of HRT on removal efficiency and discharge concentration for Jollyville. It was found that removal efficiency increased with increasing residence time ($p = 0.017$); however, this was not confirmed at any of the other sites. Discharge concentration, on the other hand, was only a function of influent concentration and HRT was not statistically significant.

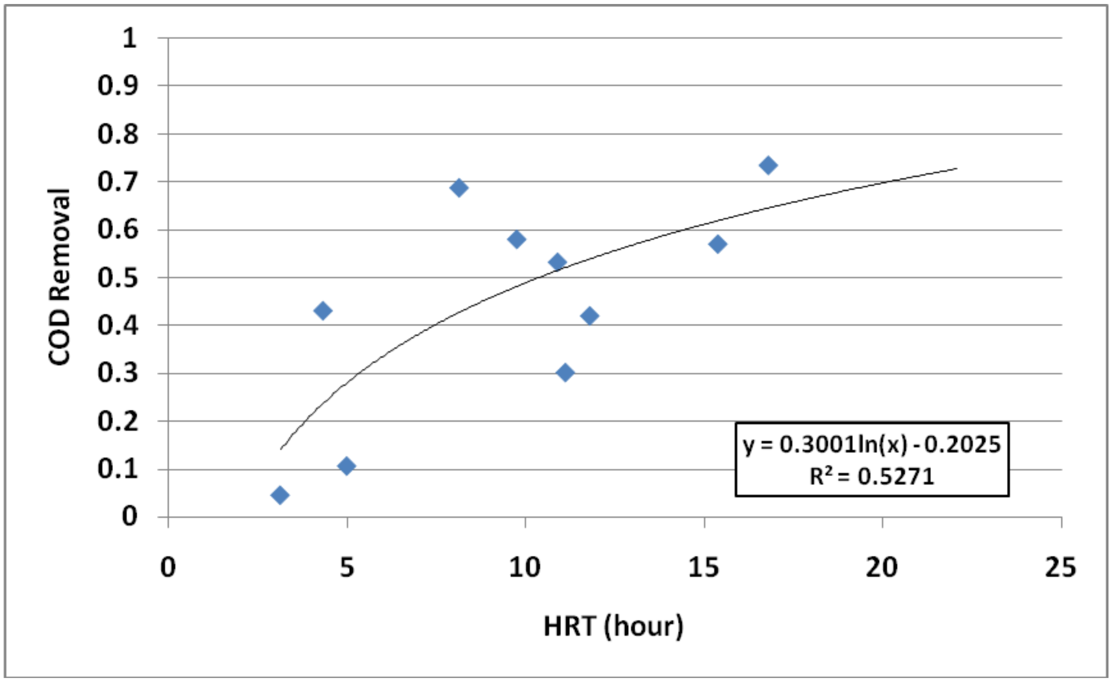

Figure 88 Relationship between HRT and COD Removal

COD Conclusions

1. Removal of COD in sand filters is statistically significant.
2. Unlike BOD discharge concentrations at Jollyville and Barton Ridge, COD concentrations tend to be higher than at the other sites, which is somewhat surprising since the two tests are generally considered to measure the same characteristic.

12 Zinc Performance

The statistical distribution of the data at the individual sites is presented in Table 24. The distributions are not clearly either normal or lognormal. Figure 89 presents the influent and effluent probability plots for the pooled paired data from all the sites. The difference between the two distributions is substantial and neither are statistically distinguishable from a lognormal distribution.

Table 24 Statistical Distribution of Zinc Data for Each Site

	Barton Mall	Barton Ridge	Brodie Oaks	Highwood	Jollyville	All sites
Influent	Lognormal/normal	Lognormal/normal	Lognormal/normal	Lognormal/normal	Lognormal	Lognormal
Effluent	Lognormal	Lognormal/normal	Lognormal/normal	Lognormal/normal	Lognormal/ normal	Lognormal

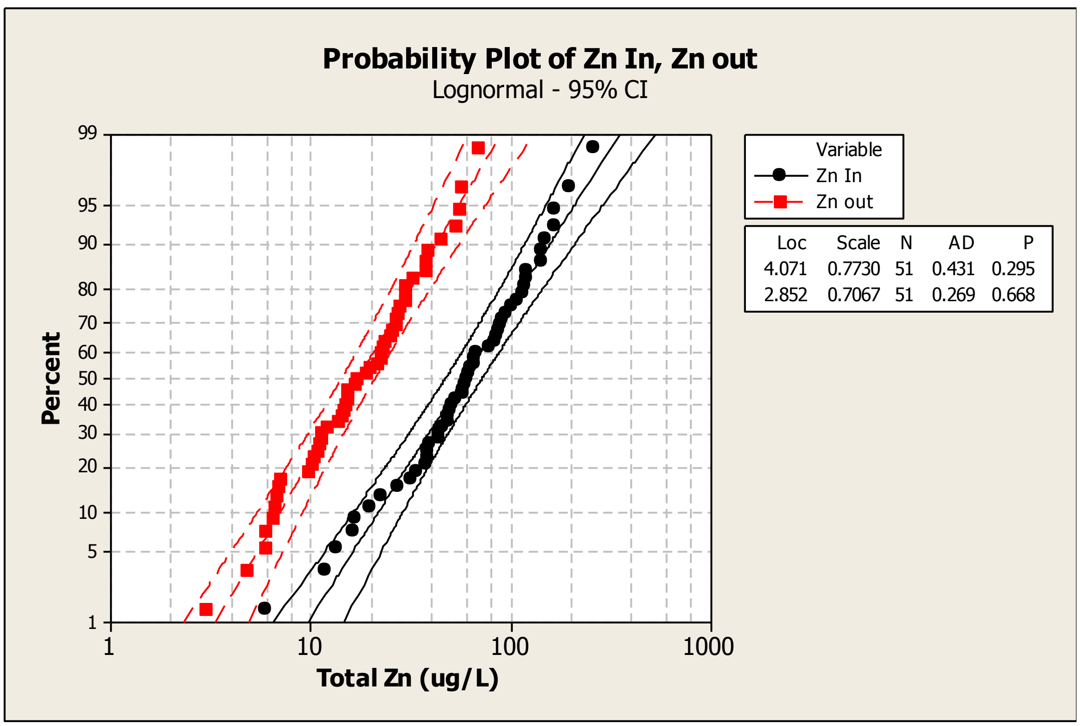

Figure 89 Zn Influent and Effluent Probability Plots

Boxplots of Zn influent and effluent concentrations for the five sand filters are presented in Figure 90 and Figure 91 respectively. Statistical analysis (ANOVA) indicates that the influent concentrations are significantly different (p = 0.016), with the highest values being observed at

Jollyville. The discharge concentrations, however, are not statistically different (p = 0.566), which is what was observed for TSS.

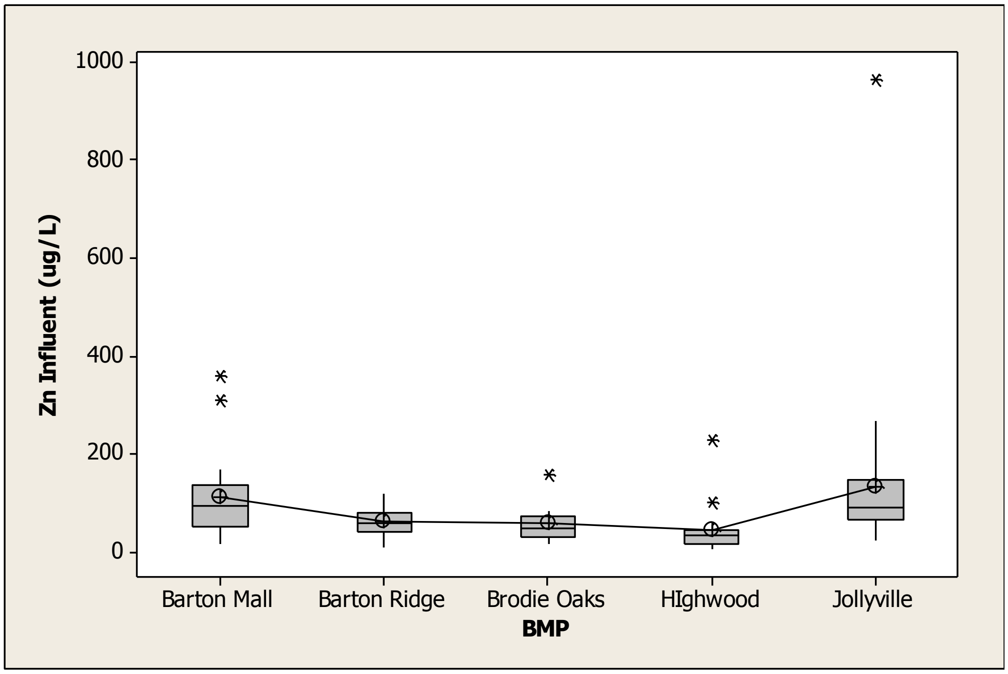

Figure 90 Boxplot of Zinc Influent Concentrations

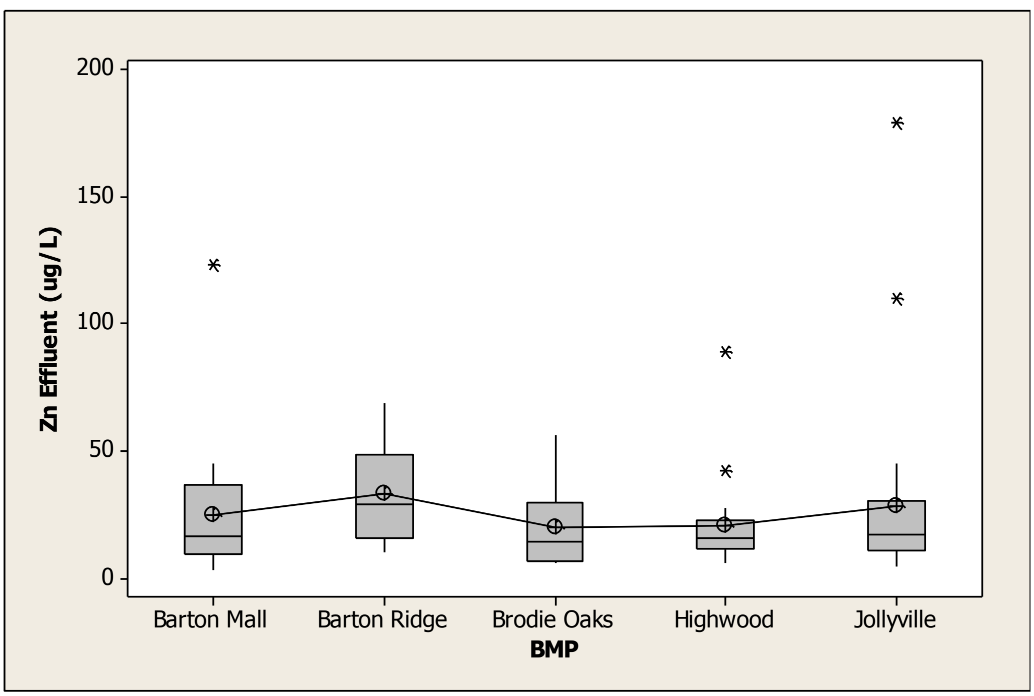

Figure 91 Boxplot of Zn Discharge Concentrations

Monitoring in the Austin area indicates that zinc in runoff is predominantly associated with particles, with the dissolved portion accounting for roughly 25% of the total (Barrett and Stanard, 2008). Complicating the analysis of Zn removal in this dataset is the fact that only the concentrations for total Zn were measured. If there are changes in Zn removal from event to event, it could be due to two very different causes – chemical reactions in the filter media or differences in the influent partitioning between the dissolved and particulate fraction. If the discharge from an event has a large concentration it could be the result of a particularly high proportion of dissolved Zn in the influent or the lack of time or other factors that would not allow the reaction to reach equilibrium. This cannot be resolved with these data.

Since the majority of zinc is associated with the particulate phase, one would expect that the removal would be somewhat less than that observed for TSS, but still particle dominated unless there was substantial removal of the dissolved component through adsorption, precipitation, or complexation. Table 25 presents average influent and effluent zinc concentrations for the five sites. Like many other constituents the sites with the highest influent concentrations tend to have the higher efficiency ratio. The particularly poor performance at Barton Ridge will be discussed subsequently.

Table 25 Zinc Concentrations for Individual Sites based on Paired Data

Site	EMC in	EMC out	Efficiency Ratio	Paired t-test
Barton Mall	127	17	87	0.002
Barton Ridge	58	38	35	0.289
Brodie Oaks	45	24	46	0.375
Highwood	27	15	45	0.039
Jollyville	107	21	81	<0.000
All Sites	84	22	74	<0.000

Figure 92 presents the relationship between influent and effluent concentrations for Zn. Unlike the graph for TSS, there is little increase in discharge concentrations at higher influent concentrations. It is interesting to note that Barton Ridge consistently has some of the higher discharge concentrations, although not significantly higher. A likely explanation is the amount of galvanized material used in the construction of the facility. As shown in Figure 93, there are galvanized grates, equipment boxes, hand rails, and access ladders that are potential sources of zinc within the BMP itself. In a study conducted for TxDOT (unpublished) samples of rainfall dripping from a galvanized bridge rail were collected and concentrations of Zn ranged from 9480 μg/L to 3260 μg/L; consequently, the construction materials at this site are likely responsible for the somewhat elevated concentrations observed. The effect of these materials should be somewhat muted, since they only contribute zinc during the storm itself and not during the subsequent days required to fully drain the facility.

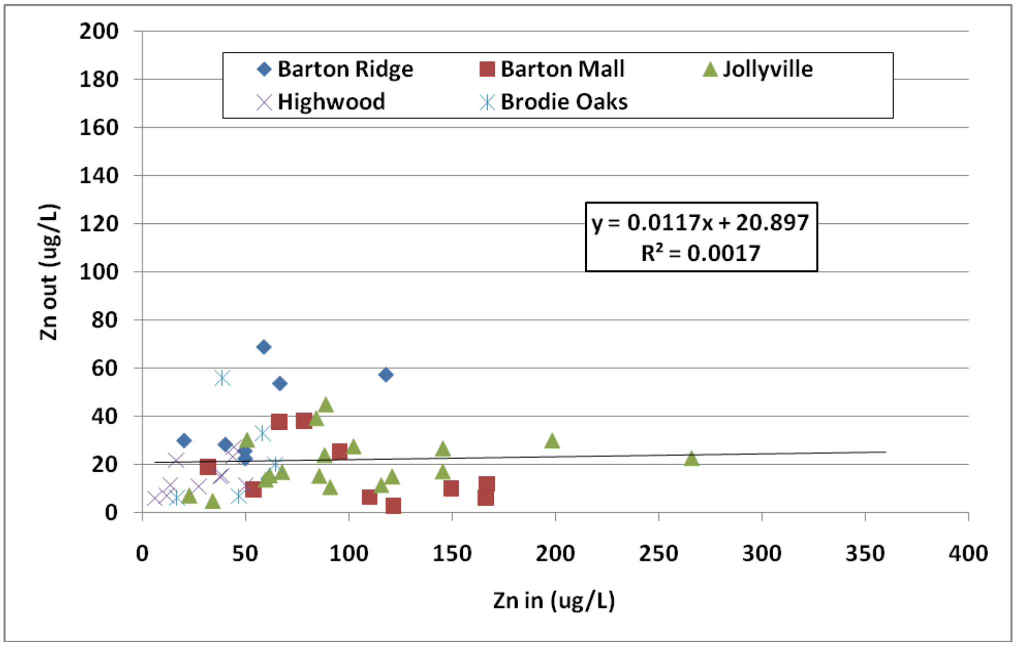

Figure 92 Relationship between Zn Influent and Effluent Concentrations

Figure 93 Photograph of the Barton Ridge Sand Filter

The time series of Zn discharge concentrations observed at the Jollyville are presented in Figure 94. The first flush effect that was so dominant for TSS is much more muted for zinc. A working hypothesis based on the results from the TSS analysis is that zinc is not associated as strongly with the particles trapped in the underdrain. This could be because it is not associated strongly with that particle size class or that the particles zinc is associated with are less dense and not as prone to settling in the underdrain. One major source of zinc in stormwater runoff is rubber from tire wear, since zinc oxide constitutes approximately 1 - 2% of tires by mass (Shaheen and Boyd, 1975). Consequently, the zinc may be attached more strongly to rubber particles that are less dense and therefore do not settle as readily or that are somewhat larger than can pass through the filter.

A comparison can also be made of the removal of Zn that occurs in the sedimentation basin relative to the filtration basin at Barton Ridge. This comparison is strongly affected by two EMCs that seem to be far higher than any others observed. These measurements were for Events 19940808A (single aliquot) and 19950907A (two aliquots). Eliminating these two events from consideration, the comparison indicates that effectively all of the Zn removal occurs in the sedimentation basin. The mean concentration in the discharge from the sand filter is actually slightly higher than the sedimentation basin discharge, although the difference is not significant. Consequently, we can conclude that the particulate fraction of zinc is associated with larger, denser particles that are effectively removed by gravity separation. Overall, removal was about 50 percent for Zn. This suggests that the reason for the lack of a first flush phenomenon is the result of Zn being primarily associated with the particle size fraction that is too large to pass through the filter and collect in the underdrain system.

Figure 95 presents a graph of zinc effluent concentrations versus maximum event discharge rate for the Brodie Oaks facility, which is a surrogate for loading rate. It is apparent from the figure that some of the lowest discharge concentrations were produced during events with the greatest water depth (resulting in the highest discharge rate), so loading rate does not seem to be a significant design factor for zinc removal.

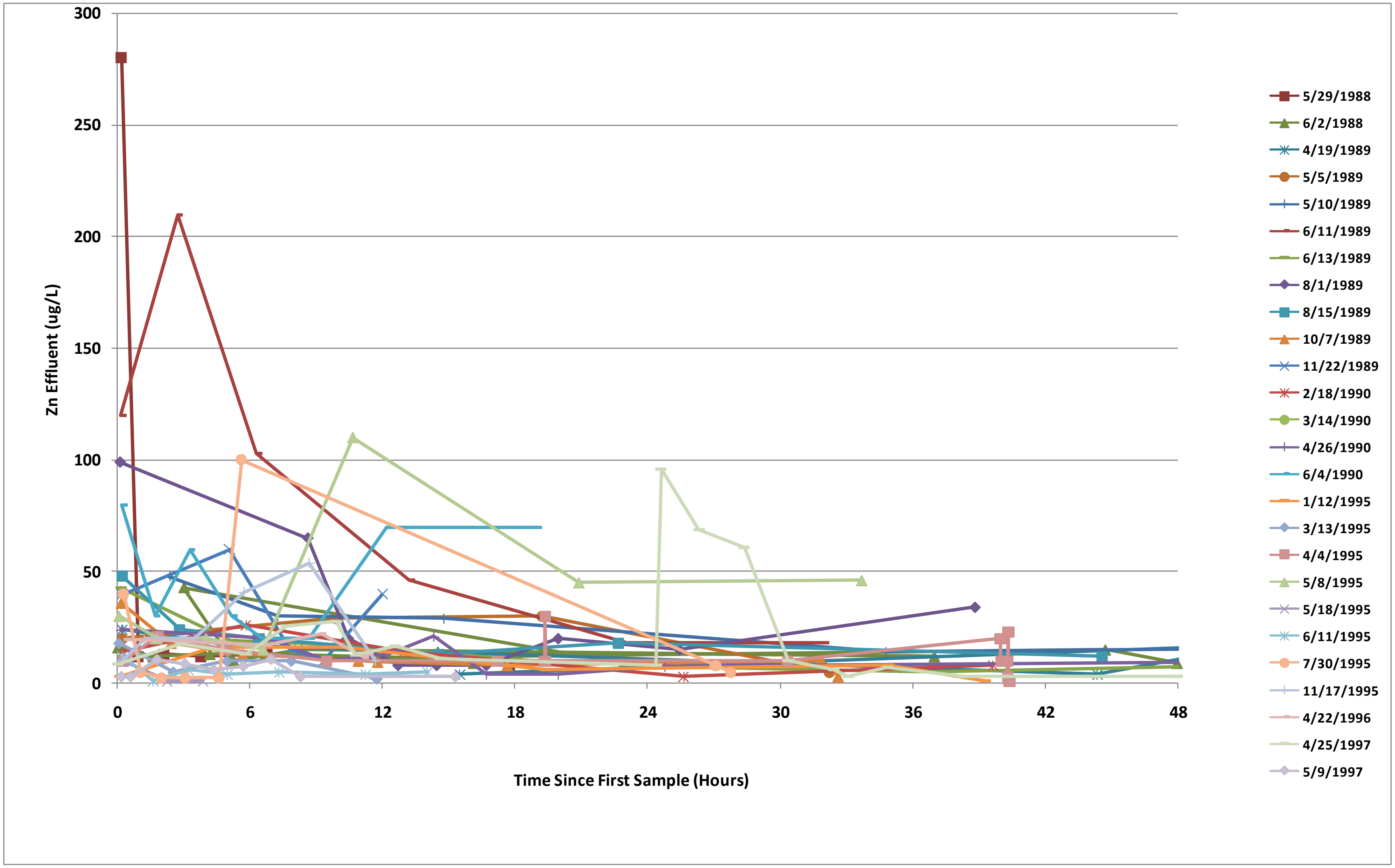

Figure 94 Jollyville Zn Time Series Discharge Concentrations

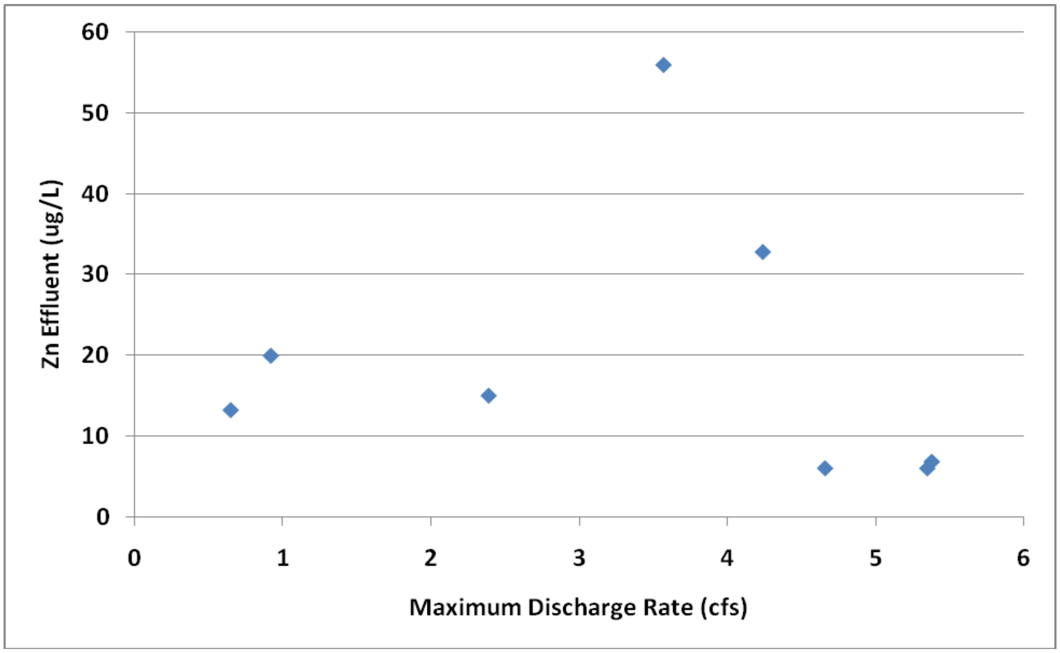

Figure 95 Relationship (or not) between Zn Discharge Concentration and Discharge Rate

HRT would be expected to player a more prominent role in zinc removal, since some fraction is in the dissolved phase and removal might be expected to improve with increased time for precipitation, complexation, or adsorption. Figure 96 presents a comparison of discharge concentrations and HRT; however, the relationships between those two variables or between HRT and removal efficiency are not statistically significant.

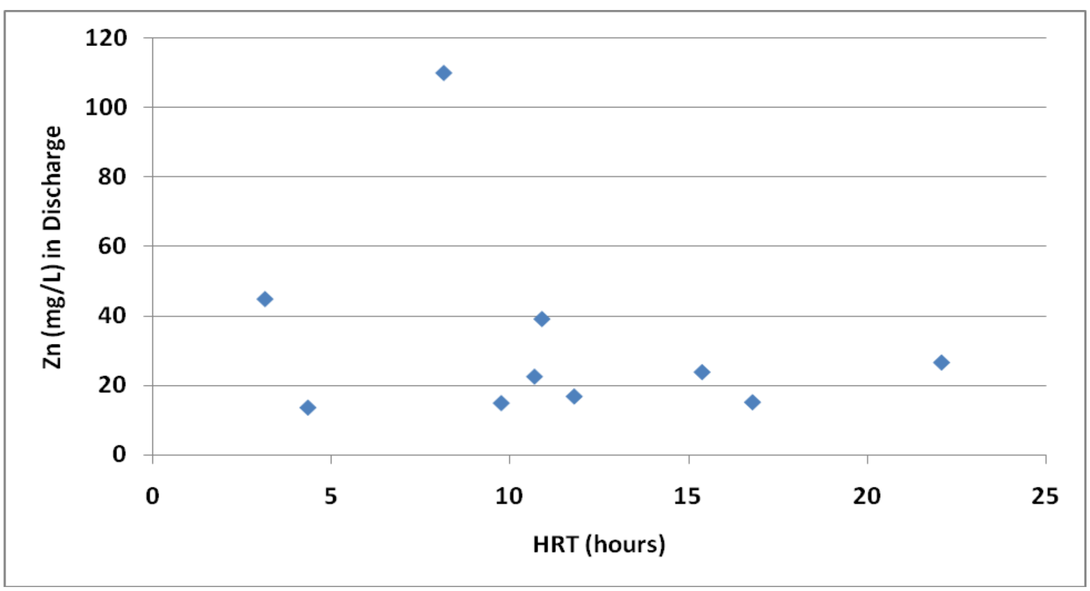

Figure 96 Relationship between HRT and Zn Discharge Concentration (Jollyville)

Zinc Conclusions:

1. Zinc discharge concentrations are relatively constant throughout the duration of an event and do not exhibit the first flush effect evident for TSS.

2. Zinc discharge concentrations are independent of influent concentrations and average about 20 μg/L.

3. Zinc fixtures within a BMP result in a noticeably, but not significantly, higher discharge concentration.

4. Discharge concentrations are not correlated with hydraulic loading rate.

5. Removal efficiency and effluent concentrations are not significantly correlated with hydraulic residence time.

13 Copper Performance

The statistical distribution of the copper concentrations for the individual sites are presented in Table 26. Cumulative probability plots were prepared using the paired data from all the sites. These are presented in Figure 97. The distributions are distinctly different, which reinforces the conclusion that significant removal does occur in sand filters, and they are lognormally distributed.

Table 26 Statistical Distribution of Copper Data for Each Site

	Barton Mall	Barton Ridge	Brodie Oaks	Highwood	Jollyville	All sites
Influent	Lognormal	Normal/lognormal	Lognormal/normal	Lognormal/normal	Lognormal/ normal	Lognormal
Effluent	Lognormal/normal	?	Lognormal/normal	Lognormal/normal	Lognormal	Lognormal

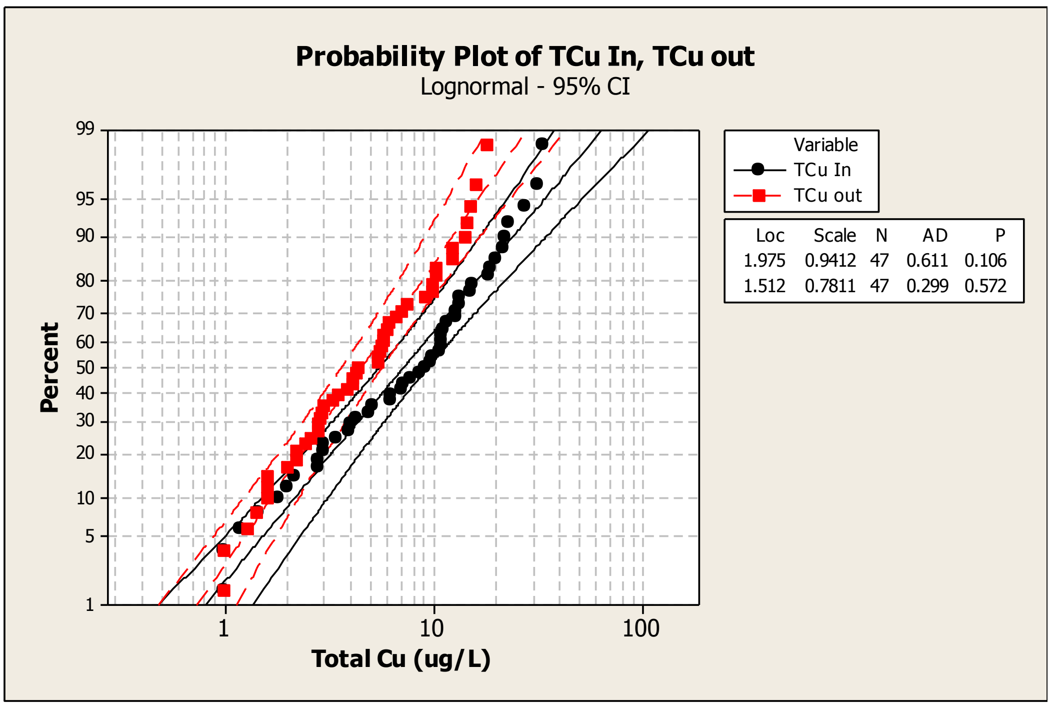

Figure 97 Probability Plots of Total Copper Influent and Effluent

Boxplots of total copper concentration for the five sites are presented in Figure 98 and Figure 99, respectively. The influent concentrations are distinctly different ($p = 0.001$); however, the analysis indicates that the effluent concentrations are only moderately different ($p = 0.107$).

Interestingly, if only the storms are used for which paired data are available the ANOVA indicates almost no difference at all (p = 0.936), which indicates that all the sites produce very similar effluent concentrations.

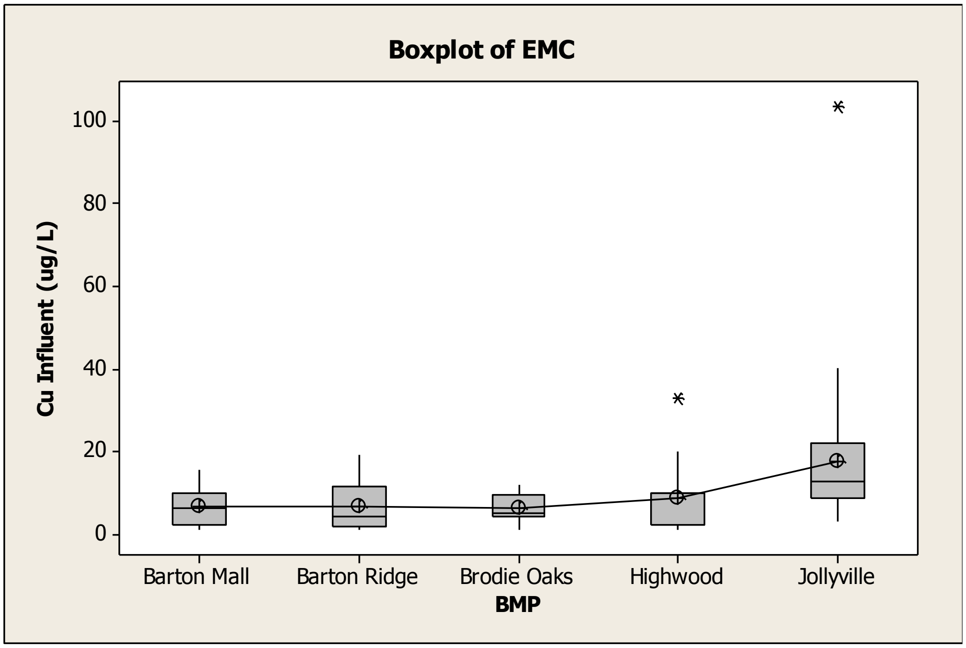

Figure 98 Boxplot of Cu Influent Concentrations

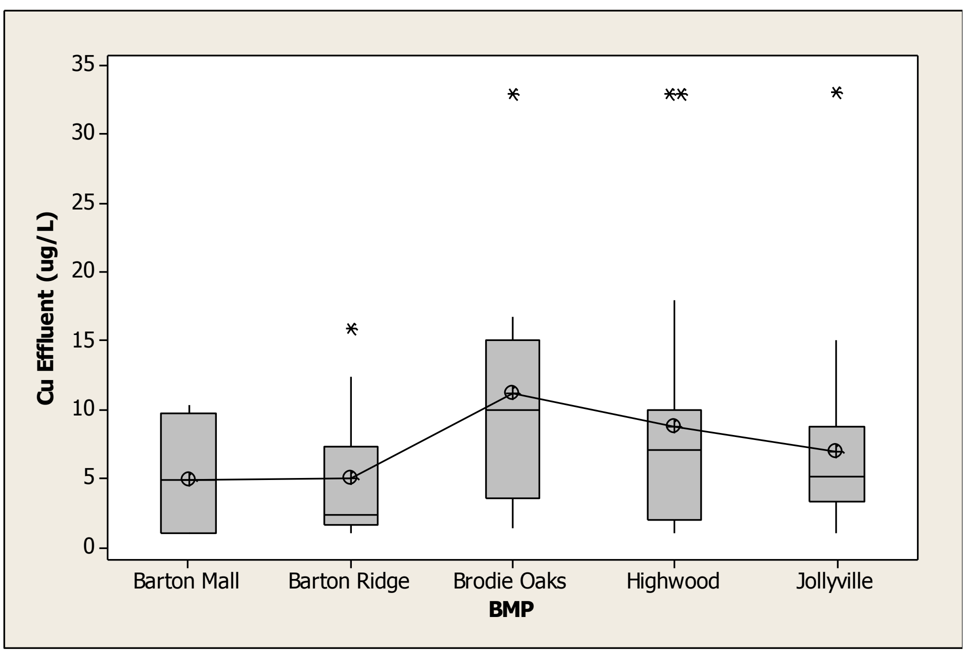

Figure 99 Boxplot of Copper Effluent Concentrations

Mean influent and effluent copper concentrations for the five sand filters are presented in Table 27. In general, there is only modest removal, but the influent concentrations are very low. It appears that the average discharge concentration is approximately 6 μg/L, which is very similar to the influent concentrations at many of the sites.

Table 27 Copper Concentrations for Individual Sites based on Paired Data

Site	EMC in	EMC out	Efficiency Ratio	Wilcoxon SRT
Barton Mall	6.5	5.1	22	0.5078
Barton Ridge	7.3	6.2	15	1.000
Brodie Oaks	6.0	5.0	17	0.625
Highwood	7.8	6.7	14	1.000
Jollyville	15.3	6.3	59	<0.000
All Sites	10.4	6.1	42	<0.000

A regression analysis was performed on the paired data for all the sites to determine if there is a significant relationship between influent and effluent concentrations. This relationship was determined to be statistically significant ($p < 0.000$). The regression was also significant for all the individual sites except Barton Ridge, even though Jollyville was the only facility with statistically significant removal. These regressions are presented in Figure 101 through Figure 104.In addition, HRT was also considered as a predictor for the Jollyville data; however, it was not significant (0.377).

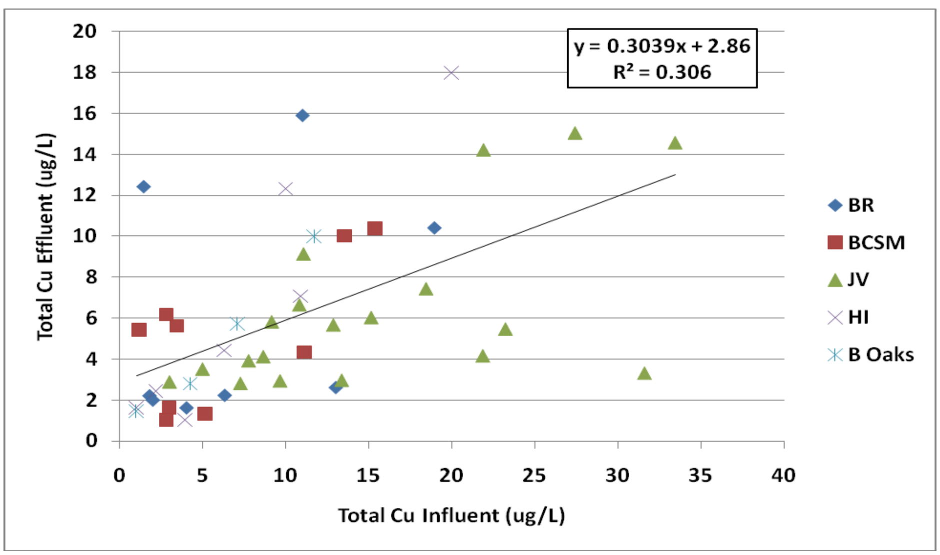

Figure 100 Relationship between Total Copper Influent and Effluent Concentrations

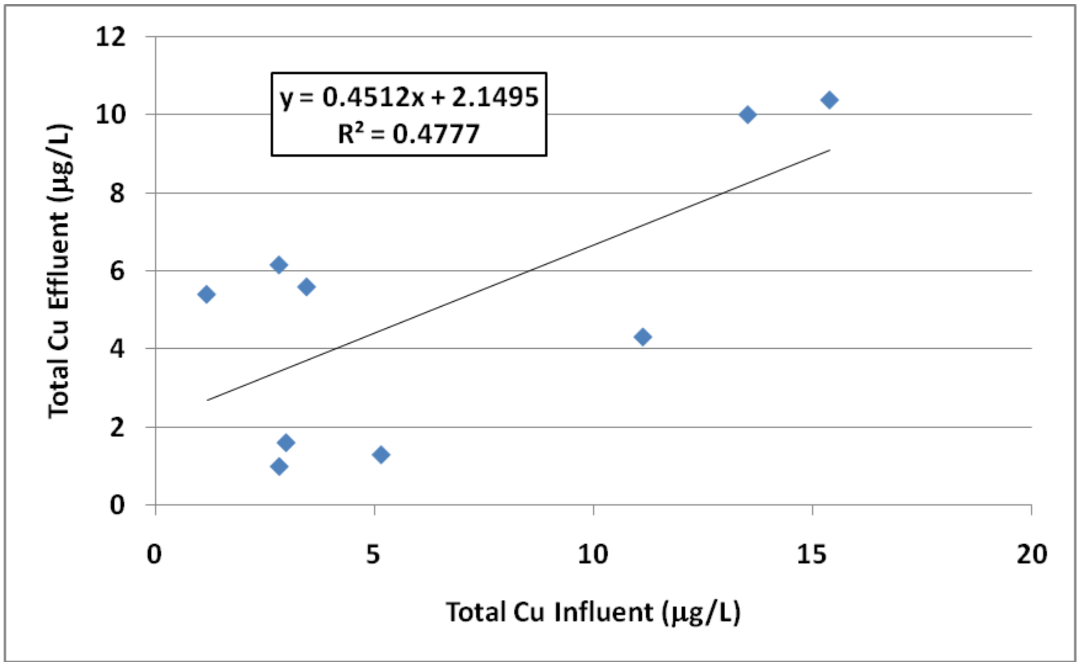

Figure 101 Relationship between Total Cu Concentrations Barton Mall

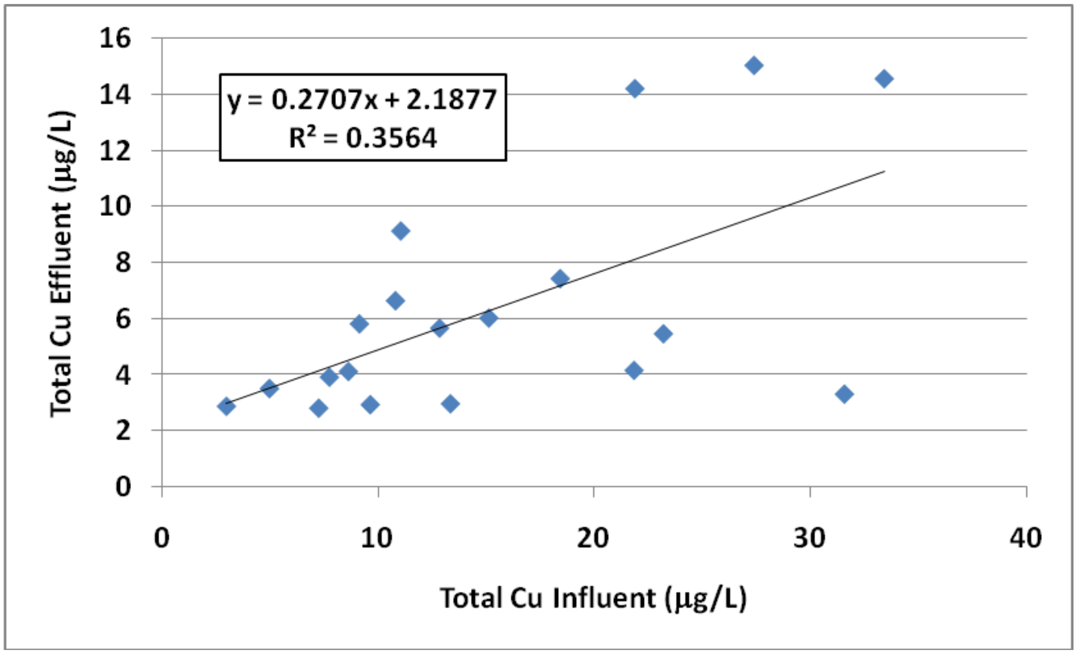

Figure 102 Relationship between Total Cu Concentrations Jollyville

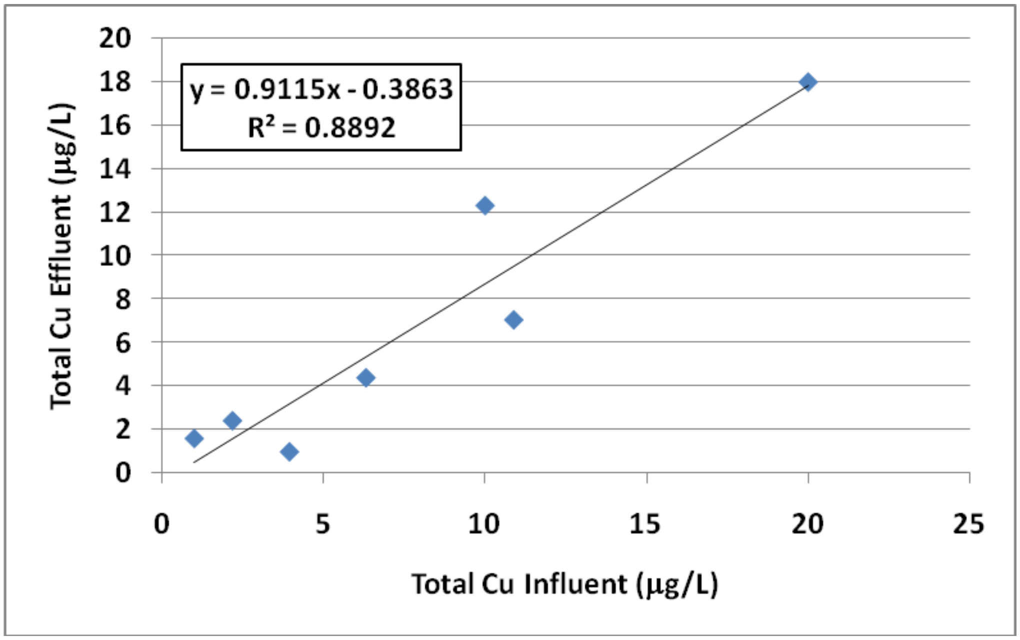

Figure 103 Relationship between Total Cu Concentrations Highwood

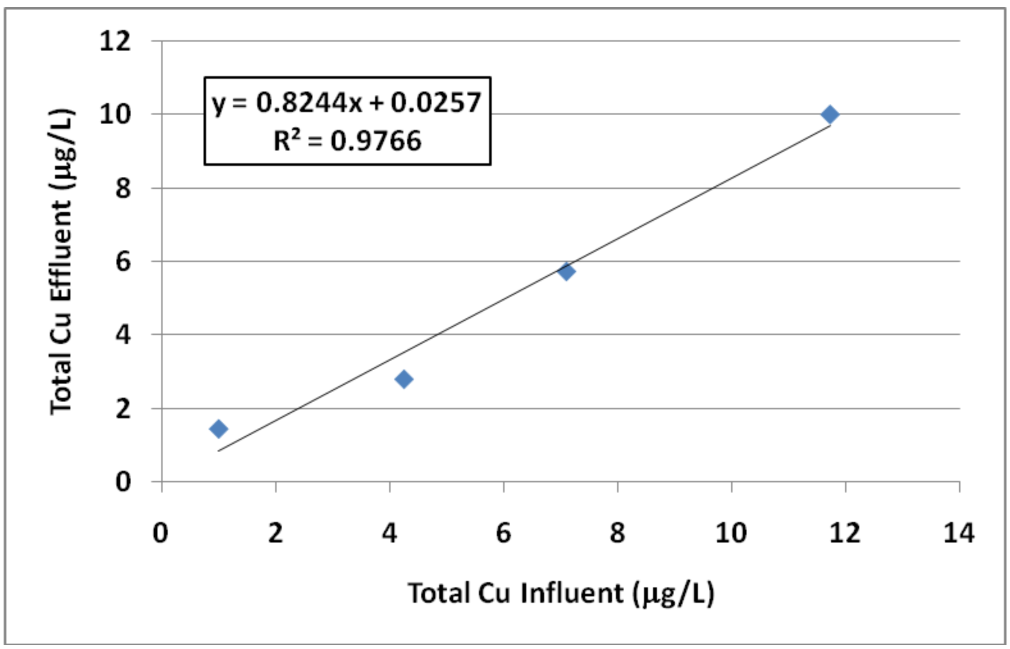

Figure 104 Relationship between Total Cu Concentrations Brodie Oaks

The temporal pattern of copper discharge concentrations at Jollyville, which are presented in Figure 105, are very similar to those observed for zinc. There is a subdued first flush effect, but most events have relatively constant discharge concentrations.

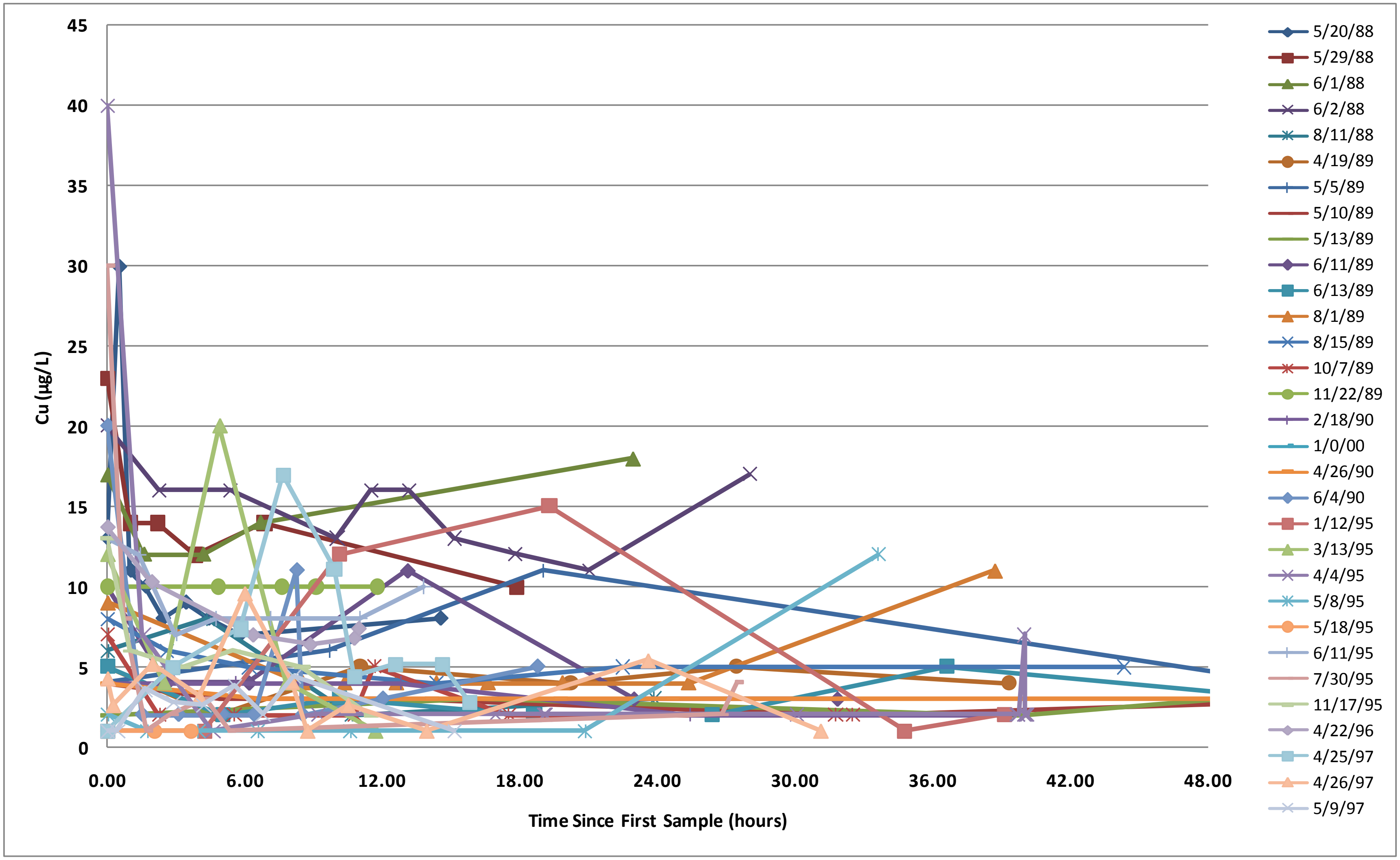

Figure 105 Temporal Pattern of Copper Discharge Concentrations at Jollyville

Copper Conclusions:

1. Little copper reduction was observed at most of the sand filters; however, average influent concentrations were very low.

2. Behavior of copper appears to be very similar to zinc.

14 Lead Performance (Pb)

Table 28 presents the results of the analysis of statistical distribution for each of the sites individually. The observed data are both normally and lognormally distributed. Cumulative probability plots for influent and effluent lead concentrations are presented in Figure 106. The distributions are very distinct, which supports the finding that significant reductions in concentration occur in sand filters.

Table 28 Statistical Distribution of Lead Data for Each Site

	Barton Mall	Barton Ridge	Brodie Oaks	Highwood	Jollyville	All sites
Influent	Normal	Lognormal/normal	Lognormal/normal	Lognormal/normal	Normal	?
Effluent	Lognormal	lognormal	Lognormal/normal	?	Lognormal/ normal	Lognormal

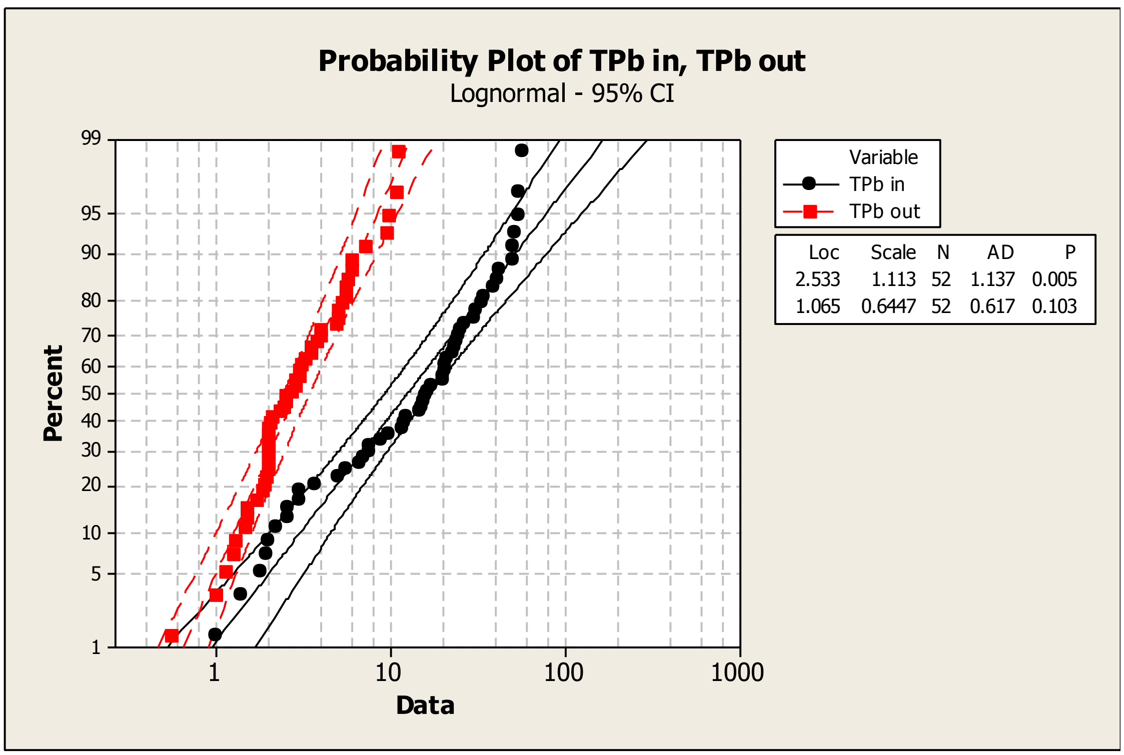

Figure 106 Probability Plots of Total Pb Influent and Effluent Concentrations

Boxplots of influent and effluent concentrations are presented in Figure 107 and Figure 108, respectively. ANOVA indicates that influent concentrations are not significantly different (p =

0.149), while effluent concentrations are somewhat different (p = 0.087). Using only paired data the effluent concentrations are not statistically different (p = 0.188).

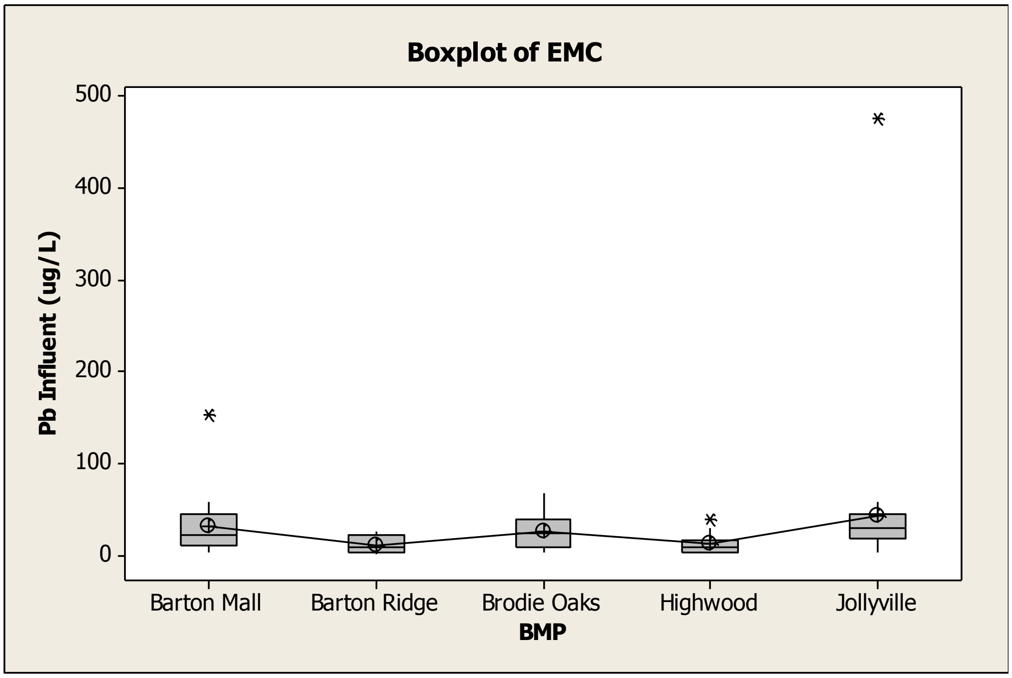

Figure 107 Boxplot of Lead Influent Concentrations

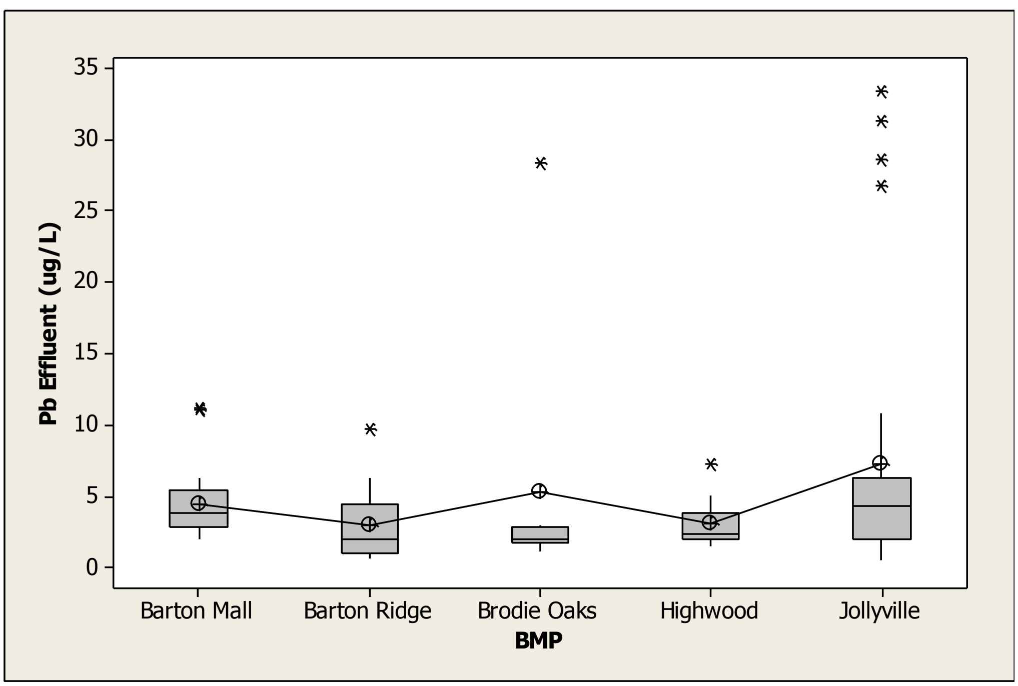

Figure 108 Boxplot of Effluent Lead Concentrations

Lead in stormwater runoff is predominantly associated with the solid phase so its removal should be similar to what is observed for TSS. The average concentrations and efficiency ratios are presented in Table 29, and it is clear that removal is substantial at all sites, although not always statistically significant.

Table 29 Lead Concentrations for Individual Sites based on Paired Data

Site	EMC in	EMC out	Efficiency Ratio	Paired t-test
Barton Mall	33	4.8	86	0.002
Barton Ridge	11.8	2.8	76	0.070
Brodie Oaks	8.1	1.9	76	0.125
Highwood	7.5	2.9	61	0.215
Jollyville	27	4	85	<0.000
All Sites	20	3.6	82	<0.000

A regression analysis was also performed to determine the effect of influent concentration on discharge quality. The results are presented in Figure 109, and they show little effect of influent concentrations. This is very similar to what was observed for TSS, which confirms our understanding that very little of the lead is in the dissolved form. On an individual basis, only Highwood showed a statistically significant relationship between influent and effluent and this relationship is presented in Figure 110.

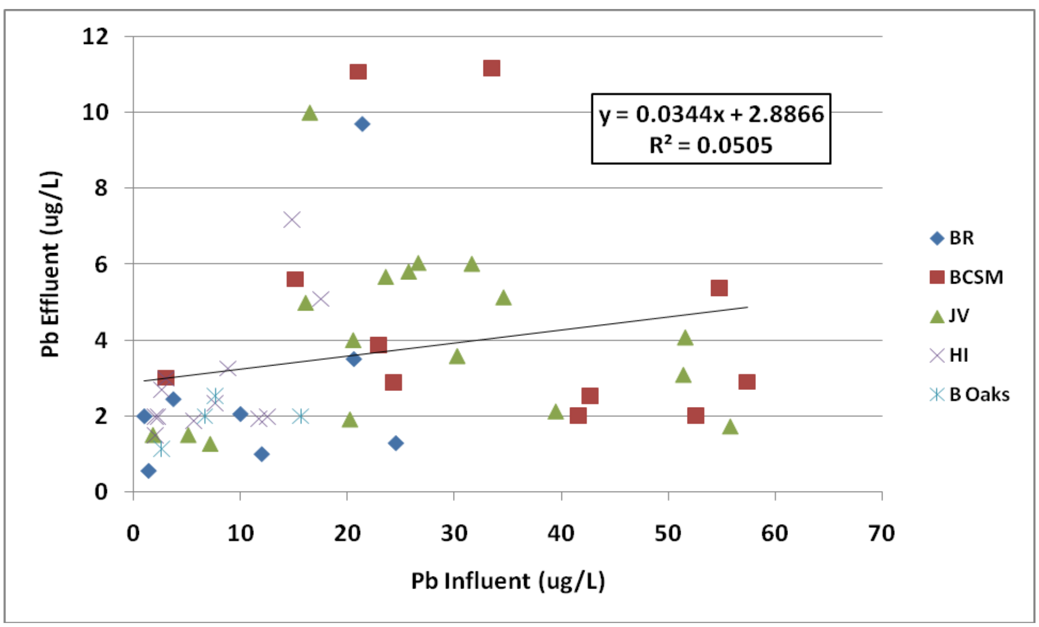

Figure 109 Relationship between Pb Influent and Effluent Concentrations all Sites

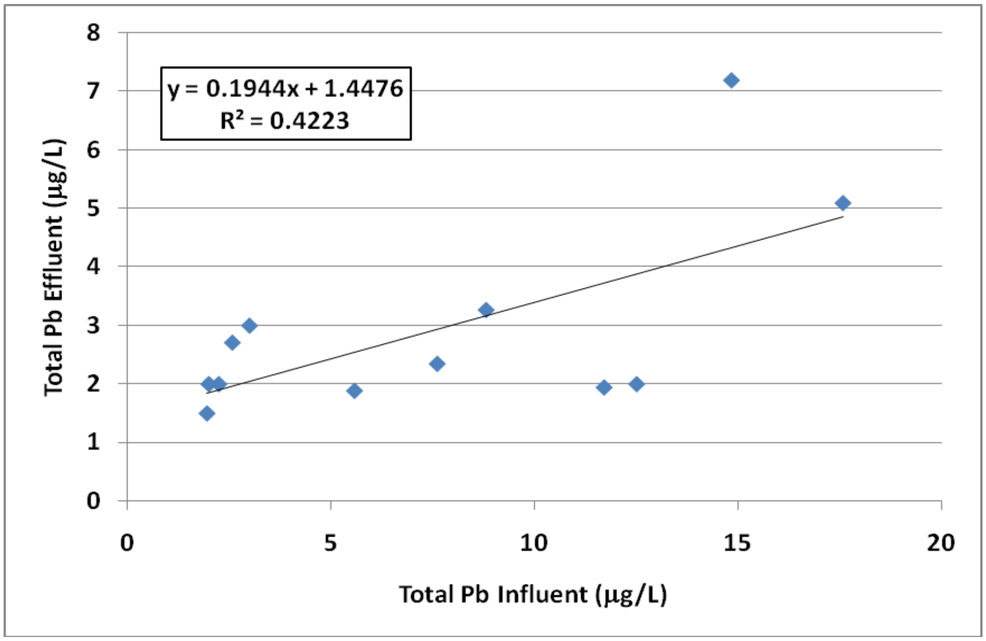

Figure 110 Relationship between Pb Influent and Effluent Concentrations Highwood

The temporal pattern of lead discharge concentrations at Jollyville are presented in Figure 111. There is little evidence of a first flush phenomenon in contrast to what was observed for copper.

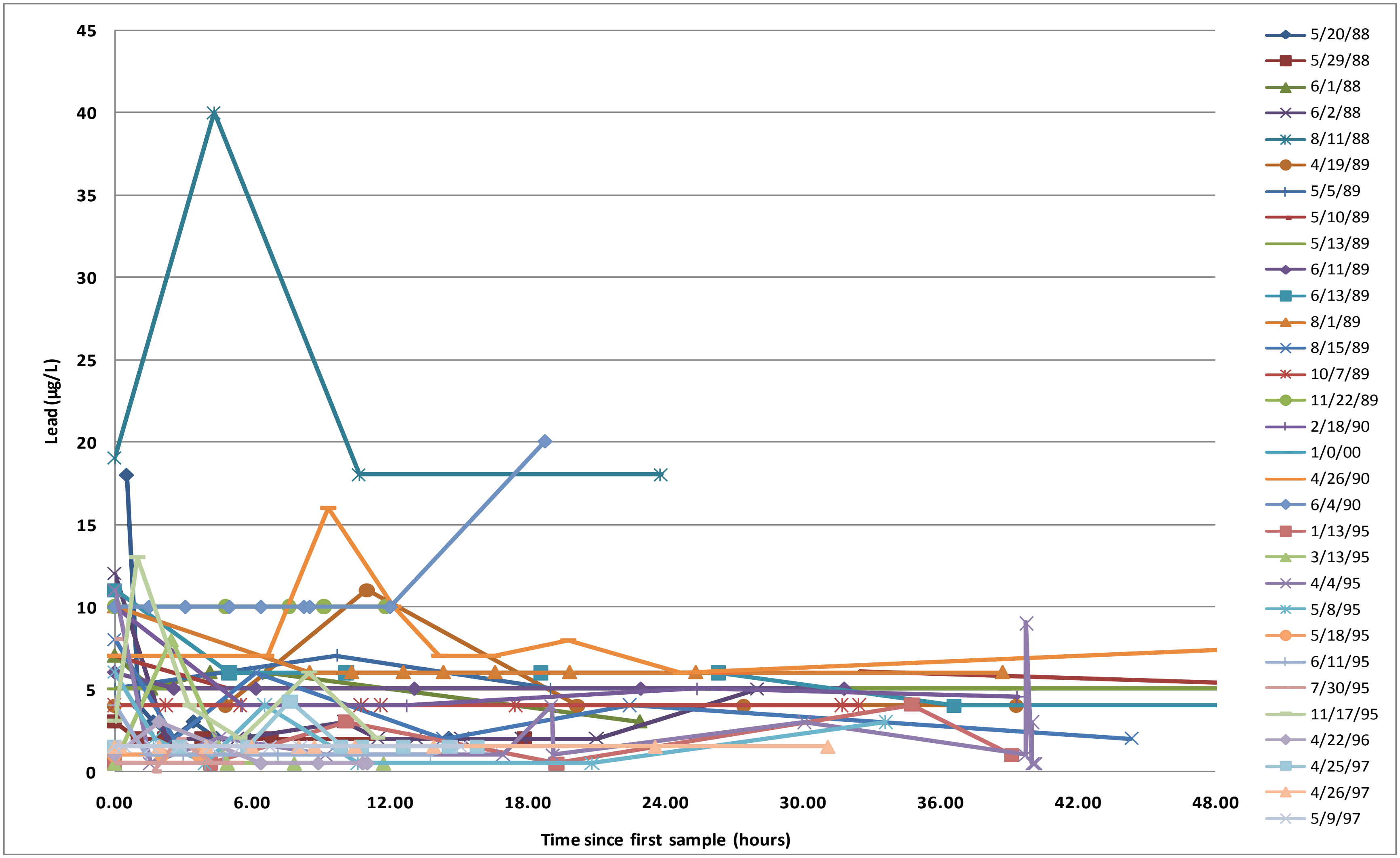

Figure 111 Temporal Pattern of Lead Effluent Concentrations at Jollyville

15 Overall Conclusions

1. Discharge concentrations for TSS, TP,TKN, Zn, Cu, and Pb were similar at all facilities, so design factors such as pretreatment, maximum water depth, and filter area apparently have little effect on pollutant removal.

2. Discharge concentrations for fecal coliform, fecal strep, and COD were correlated with influent concentrations, so differed between the sites. This suggests that a substantial amount of these materials are associated with the finest particle fraction (or dissolved in the case of COD) that can pass through the filter media.

3. Nitrate + Nitrite concentrations were significantly lower at Highwood, which might be related to the extremely small filter media volume that provided less opportunity for nitrification and nitrate export.

4. BOD discharge concentrations were lower at Barton Ridge and Jollyville, but given the similar performance at all of the sites for the other constituents it seems likely the differences were due to influent characteristics.

5. Pollutant removal was not a function of time, indicating that the accumulation of material on and within the filter had little impact on pollutant removal.

6. Most of the constituents had a distinct first flush that might be attributed to the accumulation of sediment and associated pollutants in the underdrain system at the end of storm events. The exception was nitrate, which had a first flush that was correlated with the time since the last event, indicating nitrification was occurring in the filter.

7. In general, removal efficiency and discharge concentration were not consistently related to the hydraulic residence time. Consequently reaction kinetics did not appear to be a limiting factor in pollutant removal. One caveat is that the calculated residence time is strongly affected by the influent and effluent volumes. In many cases, substantial mass balance errors likely resulted in poor estimates of HRT.

8. Pretreatment reduces the total sediment load to the filter by about 65-70%, but may not material extend the life of the filter since much of this sediment likely is fairly coarse, which would result in little loss of permeability if it accumulated on the surface of the filter.

16 References

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